THE PROTECTION OF ELECTRIC PLANT

MODERN METHODS

BY

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PREFACE

THE development of protective devices has grown with the size of plant to be protected; but, quite naturally, this development has always been subject to some degree of lag, due to the necessity of acquiring practical operating experience before the value of any protective system or device could be gauged correctly. Reliability of isolated generating stations and of simple local distribution systems is easily achieved by comparatively simple means. The larger a system becomes, both in respect of its capacity and extent, the more intricate are the causes and phenomena of disturbances, the more grave their consequences, and the more difficult the determination of suitable remedies.

An overwhelming amount of ingenious research work has been done by engineers of all countries in the attempt to make the supply of electric energy as reliable as is essential for a commodity that has become of fundamental importance in modern economics, and, indeed, to life itself. While this work was being done, a simultaneous growth of plant and systems took place, so that often a new system of protection was obsolete by the time it began to be applied in practice. The history of this rapid development during the past decades can be described as a race between the design of plant and the development of means for its protection.

It has been said above that the development of protective gear followed the growth of plant not without a certain time lag. Therefore, protective gear has never been fully adequate when and where power systems were in a state of rapid growth. This can be observed at present in this country, where recent events have shown that a failure of supply over large areas is still far from a remote possibility. On the Continent, extensive h.t. networks came into operation much earlier; consequently it is only natural to expect that, as a result of actual operating experience, their protective systems have been improved, perfected and often simplified. There is a tendency in every country to disregard, to a certain extent, the experience gained abroad; a tendency which is always regrettable and never more so than when millions of pounds

are at stake. The very best device is hardly good enough for the protection of important electrical plant which, nowadays, constitutes one of the main assets of national wealth. In this survey, therefore, an attempt has been made to explain and describe in great detail types of protective gear which have been mainly developed and produced abroad, and which are not yet as well known in this country, whereas conventional types have been referred to but briefly. Out of the great variety of protective gear, only such types are mentioned as have found wide application in actual practice.

In order to present the subject in a clear manner, separate chapters have been devoted to the main components of electrical plant, and each protective system or apparatus is dealt with in relation to its most prominent field of application. In a concluding chapter, the co-ordination of the various existing protective systems is briefly discussed, and suggestions are put forward regarding the selection of protective gear for various kinds of electrical plant.

The author wishes to make acknowledgment in general to the firms which have kindly furnished illustrations of their products; specific indication of the source from which they were obtained is made under the illustrations themselves.

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CHAPTER I

INTRODUCTION

Sources of Disturbance.—The principal sources of disturbance in electric supply systems are the following—

A. Excess Currents

1. *Earth faults*, i.e. flash-overs or permanent contact between one phase and earth.
2. *Short-circuits*, i.e. the breakdown of insulation between phases.
3. *Overload*, due either to excessive use of energy, or to persistent light faults in a part of the system.
4. *Surges* producing high currents.

The causes of *earth faults* are manifold: birds, lightning or induced excess voltage, fog, depositions of salt or dust on insulators, also trees, branches or hay, or the breakage of a conductor on overhead lines, and faulty insulation on underground cables. Earth faults may be of a permanent nature, e.g. a broken conductor touching earthed parts; or they may be temporary, with or without an arc between conductor and earth.

Short-circuits may occur between two phases or between all three phases. The total short-circuit current is supplied not only by all generators, but also by all motors in circuit. Distinction must be made between the momentary peak and the continuous short-circuit current. Fig. 1 shows a typical short-circuit current oscillogram. The respective values of the maximum momentary peak current and of the continuous short-circuit current depend on the design of the machines and the location of the fault. For modern alternators, and faults at or near the alternator terminals, approximate values for the short-circuit current at normal excitation are given in Table I. Older

types of machines may have momentary short-circuit currents up to 40 times the rated load current. The actual current in the event of a short-circuit distant from the power-station is determined by the impedance of the complete circuit.

TABLE I

APPROXIMATE VALUE OF SHORT-CIRCUIT CURRENT (TERMINAL FAULTS) as a Multiple of the Rated Current

	Turbo Alternators	Salient Pole Machines
Momentary peak (including d.c. component)	15–18 times	10–15 times
Continuous short-circuit current—		
Single-phase short	2 times	2·5 times
Two-phase short	3 ,,	3.75 ,,
Three-phase short	5 ,,	6·25 ,,

In a three-phase system, the value of the short-circuit current is not the same for a short-circuit between two phases (see Fig. 87) as for one involving all three phases (Fig. 88). If Z_l denotes the impedance of one conductor and V_f the faulty line voltage, the two-phase fault current is

$$I_f^{\text{II}} = V_f/2Z_l \qquad (1),$$

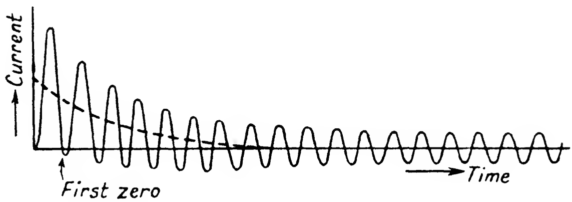


FIG. 1. TYPICAL OSCILLOGRAM OF SHORT-CIRCUIT CURRENT

whereas in the event of a fault on all three phases the currents in the three conductors are 120° apart. The current in each conductor is, therefore,

$$I_f^{\text{III}} = V_f/Z_l\sqrt{3} \qquad (2).$$

Assuming equal values of V_f in both cases, it appears that the two-phase short-circuit current is 13·3 per cent less than the current in case of a three-phase fault.

Special consideration is required in case of short-circuits comprising two phases and earth. The simultaneous earthing of two phases leads to a "two-phase short through earth" if the

two faults are close together, or to a "two-phase earth" if they are some distance apart.

High *surge* currents occur mainly in consequence of switching operations. The starting current of induction motors, or transformers with open-circuited secondary winding, may be a multiple of their rated full-load current. Where the rise is so large as to upset stability, means must be provided for the reduction of the surge current. In the past the incorporation of

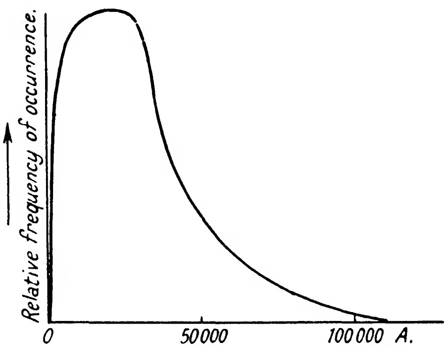


FIG. 2. LIGHTNING CURRENT OBSERVATIONS

a resistance step in the appropriate circuit-breaker was a common practice; in modern plant auxiliary biasing or time elements are incorporated in the protective relays in order to prevent their action under transient surge conditions.

B. EXCESS VOLTAGE

1. External, due to lightning or atmospherically induced charges.
2. Internal, due to switching operations or flash-overs.

Excess voltages may also be classified as static charges, and travelling waves or surges.

The most dangerous excess voltages are those caused by lightning. In order to obtain an insight into the nature of lightning, and more particularly in order to measure the current discharged to earth through a flash of lightning, systematic research work has been carried out in U.S.A. and Germany,* the results of which are reproduced in Fig. 2. The highest current ever observed was about 100 000 A.

* See Bibliography, Nos. 59 and 61.

If lightning strikes the earthed system, i.e. steel towers or earth wires, their potential may rise to a dangerous point, and cause a "backward" flash-over from a tower to a conductor, unless the towers are so well earthed that the charge can be led off to earth with a time lag smaller than the time lag of a flash-over.

Surges caused by lightning have a steep front of slope of, say, 300 kV per microsecond, and a peak value up to the surge flash-over value of insulation, which is usually about ten times the

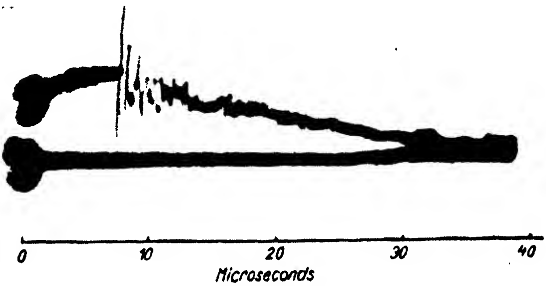


FIG. 3. TYPICAL SURGE CAUSED BY LIGHTNING

r.m.s. voltage of the system for lines carried on steel towers, and in the order of 500 kV for lines on wooden poles. Higher peak voltages lead to an immediate discharge to earth. This discharge takes place at a weak spot of the line, i.e. normally at one or several insulators.

A typical lightning surge is illustrated in Fig. 3. At open feeder ends the peak voltage is doubled by reflection. A lesser increase takes place wherever a surge is prevented from free travel by an impedance in series with the line.

C. HARMONICS. Where harmonics find an oscillating circuit, they are liable to cause damage by overheating. Higher harmonics, in spite of being suppressed as far as possible by careful design of machines and transformers, make themselves felt in practical operation under certain conditions, e.g. during light load periods when few transformers (now acting as frequency changers) are feeding into long transmission lines*. High frequency oscillations caused by arcing are another source of trouble.

* See *E.T.Z.*, 1933, p. 747.

D. Power Oscillations. Stability problems are of primary importance in networks fed from more than one generating station. In such systems every heavy fault threatens to upset stability, and it is, therefore, necessary to study the performance of protective systems from the point of view of maintaining stable parallel operation.

General Remarks. It was recognized at an early date that it is not possible to deal separately with each of these evils, as they frequently interact on each other. For this reason it is not convenient to discuss separately, and indicate a remedy for each individual trouble. An attempt is made below to give a brief outline of the present state of development of protective means, considering all parts of electric plant, from the power station through e.h.t. and h.t. transmission and l.t. distribution, to the consumer, with special reference to those devices and systems which are not yet in general use in this country.

The ultimate aim of protection is twofold. In the first place the plant itself, and in particular its most valuable and vulnerable components, must be freed from danger from any of the sources enumerated above. Secondly, the continuity of supply to the consumer must be maintained. The first requirement is, as a rule, met by isolating as quickly as possible the section affected by the fault from the remainder of the system; in order to comply with the second condition, such interruptions should be limited both locally and in respect of time, and should occur only if a fault is of a dangerous nature. Modern protective gear must therefore be capable of discriminating whether and when a fault becomes dangerous.

Protective gear also comprises such devices as render certain faults harmless or even eliminate them altogether, before any other protective apparatus comes into operation. By tackling the problem from this angle, i.e. by subduing a fault at its source, the operation of a system is freed from the confusion and unsteadiness which frequent operation of the automatic protective equipment naturally entails. Here again it is not possible to discuss separately preventive and protective gear, as it will be noticed that both are sometimes closely related or even identical.

As far as protective features form part of the lay-out and design of the machinery or apparatus to be protected, they fall outside the scope of this survey, which is thus limited to—

(*a*) devices reacting to certain fault conditions; and

(*b*) those actually performing the isolation of a dangerous fault, when called upon to do so by the former. In some cases (fuses, Petersen coils, excess voltage arresters) both the controlling and the operative device are one and the same.

Elements of Protective Gear. Before broaching the subject itself, a few words may be said about the main elements at the disposal of the engineer when planning a protective scheme.

Most of the elements employed in protective gear are familiar. Solenoids, contacts, resistances, arc gaps, small motors (including the Ferraris type), mechanical and electric time lag devices, instrument transformers, choking coils, thermometers and floats are, perhaps, the most important.

FIG. 4. URANIUM DIOXIDE RESISTANCE (*A.E.G.*)

RESISTANCES. Some words should here be said about resistances. Apart from those with constant ohmic value there are others of varying characteristics, which find useful application in connection with protective gear. Most metals have practically a constant resistance, varying only slightly with the temperature, in accordance with the equation

$$R_\tau = R_0 (1 + \alpha\tau) \quad . \quad (3)$$

where R_0 is the resistance at a certain standard temperature, R_τ the resistance at τ degrees, and α the temperature coefficient of resistance, which is, as a rule, positive. Certain materials, e.g. red hot iron wire, have such a high positive coefficient that their resistance increases practically in proportion with the voltage, thus keeping the current constant. In order to prevent oxidization, they are normally installed in glass bulbs filled with hydrogen.

On the other hand, materials are also known having a negative coefficient; their resistance decreases with increasing temperature. Fig. 4 shows an uranium dioxide resistance in a

nitrogen-filled tube; this type of resistance will stand continuous heating, up to several hundred degrees centigrade, when its resistance is approximately one-fiftieth of that in the cold condition.

Other resistances having a negative temperature coefficient are those composed of carbon powder, or liquid resistances filled with a zinc chloride solution.

Further, there are materials made of a ceramic base and by similar processes, such as "S.A.W." and "Thyrite," with characteristics depending not on temperature, but on the voltage across the resistance terminals. The current through these increases much more rapidly than the terminal voltage imposed, according to the equation

$$I = V^n/K \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (4)$$

or

$$R = K/V^{n-1} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (4a)$$

where n varies between 3 and 5 with the types of material actually employed in modern practice.

Current and Potential Transformers. Elements of considerable importance with almost every kind of protective system are the current transformers, which must combine adequate thermal and dynamical properties with a sufficient degree of accuracy in operation under fault conditions. It is not always sufficiently realized that the best system of protection is useless unless correct secondary currents are supplied to the relays, particularly in the event of heavy faults. The warning contained in B.S.S. No. 81—1927 regarding the selection of suitable current transformers is comparatively brief; but in foreign standard specifications determining factors have been established which, if systematically applied, will be found very useful when planning protective equipment. Short definitions of the terms recommended for practical use are given below.

Rated Burden. The impedance of the external secondary circuit which may be connected without exceeding the error limits specified in the class for which the current transformer is designed.

Continuous Overload Capacity. The multiple of the rated primary current which a transformer is able to carry without exceeding the permissible temperature rise. It is sound practice to design all current transformers for a considerable continuous overload.

Dynamic Current Limit. The maximum first peak current which the transformer with short-circuited secondary can carry without suffering mechanical damage.

Thermal Current Limit. The primary current permissible for one second, without undue heating.

The secondary windings are, as a rule, not in danger, as the current in them cannot exceed 30 to 50 times the rated current, due to saturation of the core. Primary windings, in particular those for currents below 200 A, offer some difficulties in respect of the dynamic and thermal current limit. Therefore, bar-type primaries are preferable, but their output is limited. Fig. 5 shows an up-to-date current transformer having a high dynamic current limit. No oil or compound is used in this design.

FIG. 5. MODERN CURRENT TRANSFORMER WITH HIGH DYNAMIC CURRENT LIMIT (*A.E.G.*)

It must further be realized that all existing Standard Specifications for measuring transformers have been drawn up mainly with a view to the connection of measuring instruments, whereas the requirements for the connection of protective relays are often entirely different. Thus standard current transformers are designed with a view to the specified performance at values below the rated current; for the purpose of over-current protection, the performance at very high over-currents is the more important consideration. At these high currents, standard current transformers have a ratio error rapidly increasing when saturation is reached in the core, i.e. above 10 or 15 times the rated current. In order to gauge the performance of current transformers for protective purposes, the *Excess Current Factor* will be found a most useful term, i.e. the multiple of the rated current at which the ratio error amounts to a certain percentage. (The German regulations specify 10 per cent when connected to the rated burden irrespective of the power factor.) A high excess current factor and a low ratio error are essential for all current transformers used in connection with excess current relays, distance relays, and certain types of differential relays. For use with earth leakage relays, directional relays and reactance relays, a low phase error is also an important requirement.

Fig. 6 shows how the excess current figure can be increased by reducing the burden (i.e. the impedance of the secondary external circuit). For the purpose of designing a measuring transformer

the actual burden occurring under actual operating conditions should be taken into account, and not (as is often done) the

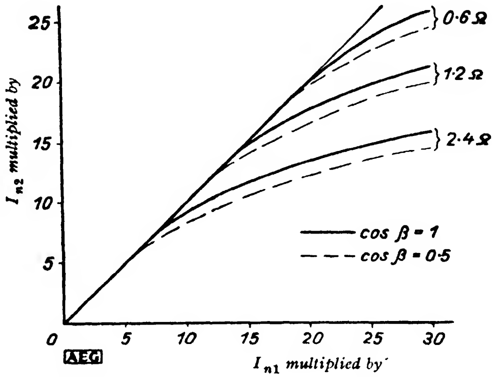


FIG. 6. INFLUENCE OF VARYING BURDEN ON CURRENT TRANSFORMER RATIO

I_{n1} – Rated primary current I_{n2} – Rated secondary current

burden at the rated secondary current. Fig. 7 illustrates the alteration of the phase error with varying currents. As a rule, phase errors within satisfactory limits are obtained up to 20 or

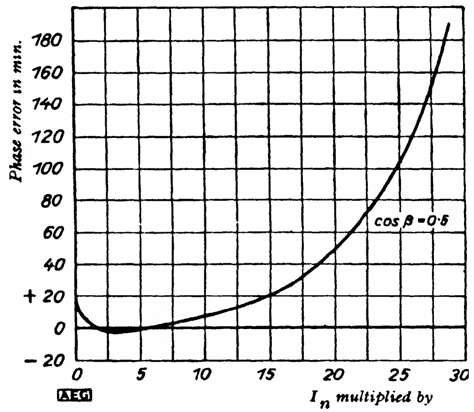


FIG. 7. VARIATION OF PHASE ERROR

I_n – Rated secondary current

30 times the rated current, with current transformers of 500 or more ampere-turns. Lower ampere-turns should, therefore, not be employed for use with directional relays. Reactance relays are

only used in systems with the highest voltages where, as a rule, the short-circuit current does not exceed 10 times the rated current; so that current transformers of lower ampere-turns may be used in this case.

The requirement to use current transformers with not less than 500 ampere-turns is not an easy one to fulfil, in particular where the primary current is low and a high dynamic current limit is wanted. A means of obtaining equal results with half the number of ampere-turns is therefore highly welcome, and much applied in modern practice. It consists in the application of a negative magnetic bias,* and is suitable for any type of current transformer.

For reasons of economy it is often desired to connect instruments and meters to the same current transformers as the relays. In this case the burden on the current transformer may become excessive while a relay operates; therefore, a short-circuiting relay (Fig. 8) is used for bridging over the current path of instruments and meters during the short periods of relay operation.

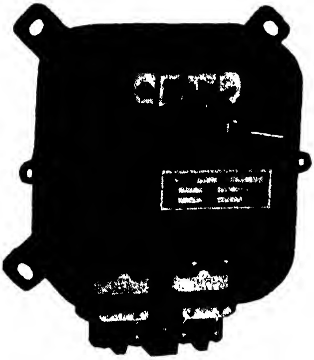


Fig. 8. Short-circuiting Relay (*A.E.G.*)

If two separate cores are used for the connection of instruments and relays, the relay core must have the high excess current figure required for its purpose. If necessary the two cores can be made of different materials and size.

When determining the necessary excess current factor for a current transformer, it is advisable to check the excess current factor of the relays to be connected. Obviously, there would be no object in installing a current transformer with an excess current factor of 20 or 30, if the respective relays were to reach their saturation at ten times the rated current.

In switchgear installations fitted with oilless circuit-breakers, it is, of course, highly desirable to keep oil or compound out of the whole installation, and therefore oilless current and potential transformers have been developed up to high voltages. It is an additional advantage that these oilless current and potential transformers may be mounted in any desired position.

* See Bibliography, No. 15, p. 100.

The star point of three-limb potential transformers must not be earthed, since the magnetic interlinkage of the three legs may lead to overheating in the event of unbalance. Where an earthed star point is required, either three single-phase transformers, or a three-phase five-limb potential transformer or equivalent type must be employed. These are also suitable for obtaining, from windings on the fourth and fifth limbs, the neutral potential (see Fig. 9).

Fuses may be used as a protection on the primary side of potential transformers, but it should be noted that such fuses,

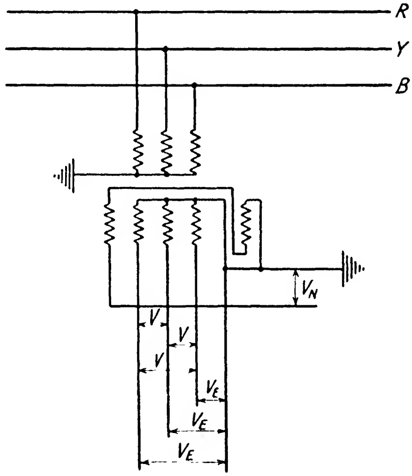


FIG. 9. CONNECTIONS OF FIVE-LIMB POTENTIAL TRANSFORMER WITH WINDINGS ON THE FOURTH AND FIFTH LEGS

V = Line Voltage
V_E = Voltage to Earth
V_N = Neutral Voltage

in order to exclude the danger of inadvertent fusing due to oxidization of the wire, should not be rated for less than 0·5 A. Such fuses, with voltages exceeding 33 kV, are merely protecting the bus-bars from a short-circuit inside the potential transformer, but are not an adequate protection for the transformer itself. Above 33 kV, a contact thermometer or Buchholz relay* is recommended for protecting potential transformers. On the secondary side, normal l.t. miniature circuit-breakers or fuses offer adequate protection.

* See Chapter IV.

The burden imposed on current and potential transformers by various types of protective relays is scheduled in Table II. When assessing the burden, the impedance of connecting leads must, of course, be added to that of the relays.

TABLE II

ENERGY CONSUMPTION OF RELAYS

Type	Burden on Instrument Transformers (per Phase)				
	Voltage Path		Current Path		Time Element, Watts
	Nominal VA at 110 V.	Ohms	Nominal VA at 5 A.	Ohms	
Tripping solenoid	—	—	7·5–75	0·3–3	—
Excess current relay with definite time lag	—	—	0·5–25	0·02–1	25–40
Excess current relay with inverse time lag	—	—	0·5–15	0·02–0·6	—
Excess current relay with multiple definite time lag	—	—	5–7·5	0·2–0·3	15–20
Intermediate relay	0·2–20	60 000–600	—	—	—
Time relay	—	—	—	—	10–150
Differential current relay	—	—	0·3–1	0·012–0·04	—
Differential wattmeter relay	5–10	2400–1200	2–5	0·08–0·2	—
Distance relay, continuous	0–30	∞–400	0·3–20	0·012–0·8	—
Distance relay, when operating	25–300	500–40	10–50	0·4–2	—
Directional relay	5–10	2400–1200	0·3–10	0·012–0·4	—
Under-voltage relay	10–15	1200–800	—	—	—
Earth relay with voltage coil	0·8–5	1500–2400	—	—	—
Earth relay with current coil	—	—	0·2–1	0·008–0·04	—
Earth relay, wattmeter type	4–18	3000–670	0·3–6	0·012–0·24	—

Classification of Protective Systems. In order to avoid confusion which may possibly arise out of the sometimes misleading denomination of protective systems, it seems advisable to introduce a uniform classification. Therefore, in Table III, the most important schemes are tabulated under four main headings. The first group, *Direct Acting Devices*, comprises all those whose action depends upon one element only, such as the current in one conductor (including split conductors), or the voltage between two phases or between one phase or neutral and earth, or the level of liquid in a tank.

The second group, *Core Balancing Systems*, comprises all protective schemes in which the factor determining their operation is the electric or magnetic unbalance caused by a fault between any number of phases at one end of a circuit. The unbalance may occur between two or more currents, voltages or other values balancing each other in normal operation.

A third group, *Differential Protection*, includes all schemes making use of a comparison between the conditions prevailing

at the two ends of the protected plant section. Pilot wires, or equivalent channels of transmission, are an inherent feature with any system under this group.

The fourth group comprises schemes in which the *direction of power flow* is the main, or only, discriminating factor for operation.

Relays. Still greater than the variety of protective systems themselves, is the number of relay designs available. The relays perhaps in most common use are of the instantaneous-acting, attracted armature type, two of which may be combined on a mutual beam for measuring the quotient of two values (balanced beam relays). Attracted armature relays are applied to simple earth leakage, split-conductor and differential protective systems, and for modern high-speed excess current and distance protection. Electro-magnetic relays with revolving armature are finding successful application in modern differential protection, particularly if fitted with biasing restraint. The induction type has been much in fashion for all kinds of applications; its low torque and inaccuracy—which incidentally increases with time—make it less suitable in connection with modern high-speed systems. For this purpose the dynamometer type is better suited. Wattmeter type relays are applied where directional features are required, e.g. for sensitive earth-fault indication. Where an accurate setting of time lag is desired, mechanical means of delay are used in preference to eddy current brakes or bimetal elements. With regard to valve relays,* no practical results are yet available.

Tripping and Reclosing of Circuit Breakers. The action of any protective relay culminates in the operation of a tripping contact. This tripping contact may either close an auxiliary d.c. circuit, break a shunt circuit energized by current transformers, or in any other way bring about the energizing of the tripping coil on the circuit-breaker.

Arrangements which incorporate tripping coils connected to the secondary winding of a power or potential transformer are not advisable, since they tend to fail when a heavy fault causes a heavy voltage drop.

A separate chapter will be devoted to the circuit-breaker itself. A device whose utilization is recently being advocated is the automatic reclosing mechanism or relay. Without doubt its application is apt to limit the duration of interruptions.

* See Bibliography, No. 7.

TABLE III

Classification of Protective Systems

Denomination	Applications A = Alternators T = Transformers F = Feeders R = Ring mains M = Multiple feeders S = Switchgear ( ) = Limited application	Types of Fault E = Earth faults S = Short circuits T = Internal faults between turns O = Overload V = Excess voltage	No. of Pilots	Remarks
(1) *Direct-acting Devices*—				
Fuse or primary relay	Small plant; rural distribution	S, E	None	Fuse may break only one phase
Current relay connected to current transformer	A, T, (F), (R)	O, S, E	,,	Only for feeders with low number of sections
Earth current relay connected to current transformer in earthing lead	T, (S)	E	,,	For ironclad switchgear only
Split-conductor systems	F, including tees	E (s)	,,	Inoperative unless insulation between splits remains intact
Split-conductor systems with standard circuit-breakers	R	E (s)	2	
Pfannkuch cable protection	(R)	S, E	None	For underground cables
Excess voltage arresters	T, S	V	,,	—
Expulsion gaps	(F, R)	V	,,	For overhead lines with solidly earthed neutral
Petersen arc suppressing coil	Avoids interruption of supply	E	,,	Not applicable to systems with graded transformer insulation
Buchholz relay	T	All internal faults	,,	—
Contact thermometer	T	O	,,	—
(2) *Core-balancing Systems*—				
Core balance earth leakage protection	F, R	E	,,	—
Excess current and earth leakage protection	A, T, (F), (R)	O, S, E	,,	Only for feeders with low number of sections,

Magnetic balance protection	*A, T, (F), (R)*	*O, S, E*	,,	do.
Distance relays in various connections	*A, T, R, M*	*O, S, E*	,,	—
(3) *Differential Protection*—				
Circulating current system (Merz-Price, etc.)	*A, T, M*	*S, (E)*	4	—
Self-balancing system (Beard)	*A, T*	*S, (E)*	3	—
Circulating-current system with current transformers in three conductors, and one in the neutral earthing connection	*T*	*E*	2	—
Circulating-current system with kick fuses or diverter relays	*T*	*S, E*	4	—
Differential protection by wattmeter relays	*T*	*S, E*	2	—
Mid-point protection (Kuyser, Beard)	*A*	*S, E, T*	3	—
Self-compensating circulating-current system	*R*	*S, E*	3	—
Split-pilot protection	*R*	*S, E*	3	—
Biased beam and related systems (McColl)	*M*	*S, E*	4–10	—
Biased differential reverse protection (McColl, etc.)	*A, M*	*S, E*	4	—
Biased circulating-current protection (McColl, etc.)	*R*	*S, E*	2–3	—
Opposed voltage system (Merz-Price)	*R* (including tees)	*S, E*	2–3	—
Opposed voltage system with sheathed pilots (Beard, Hunter)	*R*	*S, E*	3	—
Reyrolle diverter relay system	*R*	*S, E*	2	—
Translay system	*R, (M)*	*S, E*	2–3	—
Biles, Satralock system	*R*	*S, E*	4	—
(4) *Directional Protection*—				
Reverse power protection	*A*	*S*	None	Not recommended
Directional balance	*R*	*S, E*	2	—
Differential reverse power systems	*M*	*S, E*	4	—
D.C. pilot wire systems (Longfield, etc.)	*R*	*S, E*	1–2	—
Reverse power protection	*(T & F)*	*S, E*	None	For use in intermeshed low-tension networks

It has been contended, and proved by the practical experience of several American power companies, that it is indeed possible to make the time from the beginning of the fault to the first reclosing operation as low as the inherent operating time of relays and circuit-breakers.* This time is so short that lighting and heating load can be said to remain unaffected if the reclosing is successful. If the breaker is reclosed promptly, induction motors and even synchronous motors or rotary converters are given a chance to pull in without coming to a standstill. Motors of any type, however, provide a certain amount of current, feeding and maintaining an arc across the fault through a substantial number of cycles. If now the short-circuit arc is still alive when reclosing occurs, the circuit-breaker will immediately interrupt a second time. As a rule, circuit-breakers are not designed or tested for the heavy duty cycle of breaking, making and again breaking a short-circuit within less than one second. The fact that no accident has so far occurred in any of the experimental installations cannot be considered sufficient proof of reliability. It would, of course, be possible to make the application safe with the aid of a revised duty cycle for circuit-breaker tests, if immediate reclosing schemes were to find wide application. This does not seem likely, since the scheme necessitates the modification or replacement of existing relays and switchgear, and the introduction of various complications such as delayed action of under-voltage devices, field-removal relays, unloading devices, etc., in consumers' installations, if the benefit of the new scheme is not to remain limited to users of lighting and heating current.

The "initial," i.e. undelayed automatic reclosing of circuit-breakers is undoubtedly an attractive proposition, since between 70 and 90 per cent of all faults causing heavy excess current can be cleared without a noticeable interruption of the affected section. The scheme would arouse more interest were it not for the fact that better and cheaper means of protecting consumers against interruptions of supply are available. These will be dealt with in subsequent chapters.

Automatic reclosing is quite frequently adopted with a time lag of between 3 and 15 seconds before the first attempt to reclose.† A distinction is made between attended and unattended stations. Whereas breakers in attended plant are as

* See Bibliography, Nos. 80 and 81.
† See Bibliography, No. 79.

a rule only provided for a single automatic reclosing operation, those in unattended stations are made suitable for up to five automatic attempts, following one another at predetermined intervals.

The tendency to limit the duration of interruptions has also been responsible for the development of fully automatic quick-synchronizing equipments.

CHAPTER II

H.T. CIRCUIT-BREAKERS

Recent Trend of Design. The majority of all protective systems rely on the circuit-breaker for the ultimate isolation of a fault. This apparatus has not only to sustain the fault current, but also to break it within a certain time. The safety of valuable machines and transformers, and also the continuity of supply in the unaffected portion of the plant, depend upon the timely and reliable operation of circuit-breakers. The conventional, though recently improved, oil-immersed breaker, cannot be looked upon as a satisfactory apparatus, as it is liable to explode or cause fire in case of overstrain, thus becoming itself an additional source of danger to the valuable machinery which it ought to protect. For this reason, Continental manufacturers have developed oilless circuit-breakers, several thousands of which are now in successful operation, and have, in most new or modernized installations, superseded the oil-type breaker which is still prominent in this country.

In contradistinction to electric machines, transformers and most other apparatus, the design of circuit-breakers has been until recently more a matter of experience than the result of theoretical investigation. The phenomena accompanying the interruption of an arc offered considerable difficulties to scientific research, and for many years there was no other means of testing the suitability of a breaker design than by the fact that it did not fail in service.

A first attempt to obtain insight into the matter was the establishment of a short-circuit testing equipment by the A.E.G. at their Berlin Works in 1912, followed by other similar plants. But even the results of full-size short-circuit tests, and their relation to breaker performance in practice, have remained subjects of controversy up to this day, as may be gathered from the wide differences in National Standard Specifications and from numerous publications on the subject.

In spite of these obvious differences, general agreement obtained as to the choice of oil as an insulating medium, and towards the year 1926 it would seem that the explosion pot had become the recognized means for interrupting high-power

arcs. Indeed, by about ~~that time~~ 1926, sufficient experience had been acquired by leading manufacturers to enable them, despite incomplete theoretical knowledge, to construct circuit-breakers which were satisfactory from every point of view but one. This one drawback, inherent in the oil circuit-breaker, was the great amount of inflammable oil contained in the tank, which constituted a permanent source of danger.

The leading manufacturers in the U.S.A. concentrated their efforts on further improvements in the design of the approved oil circuit-breakers, with the aim of reducing their sizes. This was successfully accomplished in the oil-blast or impulse breaker (G.E.Co.) and the deion-grid type (Westinghouse).

In Germany, engineers endeavoured to get at the very root of the evil by eliminating oil altogether, and in 1926 the A.E.G. began to develop the water breaker and a little later the air-blast breaker. Siemens-Schuckert followed with their design of a breaker known under the trade name of "expansion breaker." This type uses water as a medium for voltages up to 30 kV; for higher voltages oil is normally employed.

British firms concentrated their efforts on the improvement of the design of ironclad switchgear, but on the whole stood aside in the attempts at new breaker types. This may be accounted for by the fact that until quite recently there were few extensive networks in Great Britain, and the majority of accidents in this country had not been due to oil fires or explosions, but to the touching of live parts.

The results of American development have been taken over, to a large extent, by British switchgear manufacturers. In fact, oil breakers with arc-control devices lend themselves very well to incorporation in ironclad gear and are now widely applied.

With the advent of the British Grid the required rupturing capacity of switchgear in this country has grown rapidly. Both open-type and ironclad installations are now available up to the highest voltages or ~~rupturing capacities~~. Fig. 10 shows a typical modern ironclad ~~unit with~~ circuit breaker rated at 750 000 kVA (B.S.S.) at 33 kV. Whilst the introduction of arc-control devices has reduced the amount of oil in the breaker tanks, considerable quantities of oil are contained in the bus-bar chambers, isolator chambers, measuring transformer tanks and other parts of large ironclad installations. The total mass of oil in some of the latest British power station switchgear plants

amounts to hundreds of tons, and the question arises whether there is not a heavy risk of fire involved in this practice.

The principal objection put forward in this country to the adoption of oilless circuit-breakers, such as have been developed mainly in Germany, seems to have been due to a belief that they are unsuitable for incorporation in ironclad gear; while ironclad gear itself is favoured on account of its small space requirements in comparison with open gear. As a result of recent developments, however, open installations with oilless circuit-breakers have been constructed which are smaller in overall dimensions than ironclad oil-immersed apparatus of the same capacity. Oilless breakers can be readily incorporated in ironclad gear in those cases where great importance is attached to the complete foolproof enclosure of all live parts. Fig. 11 shows the general layout of such a unit.

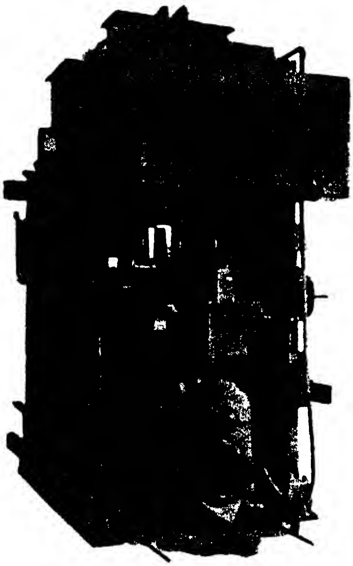


FIG. 10. TYPICAL IRONCLAD CIRCUIT-BREAKER, 33 kV
(*Ferguson Pailin Ltd.*)

Theory of Arc Extinction. Recent research has established beyond doubt that the controlled extinction of an arc requires the building up of a deionized medium between the separated contacts at a speed superior to that of the rising recovery voltage, coupled with effective cooling of the arc space. When the arc current passes zero value, the arc is, of course, interrupted. If the dielectric strength of the medium filling the arc space is sufficiently high, the arc cannot restrike and the circuit has been cleared. If, on the other hand, the dielectric strength is not yet sufficient, another half-cycle of the current will flow through the arc.

This same fundamental theory has been found to apply to any type of circuit-breaker. In a plain break oil-breaker, without any control device, ionized oil particles fill the main

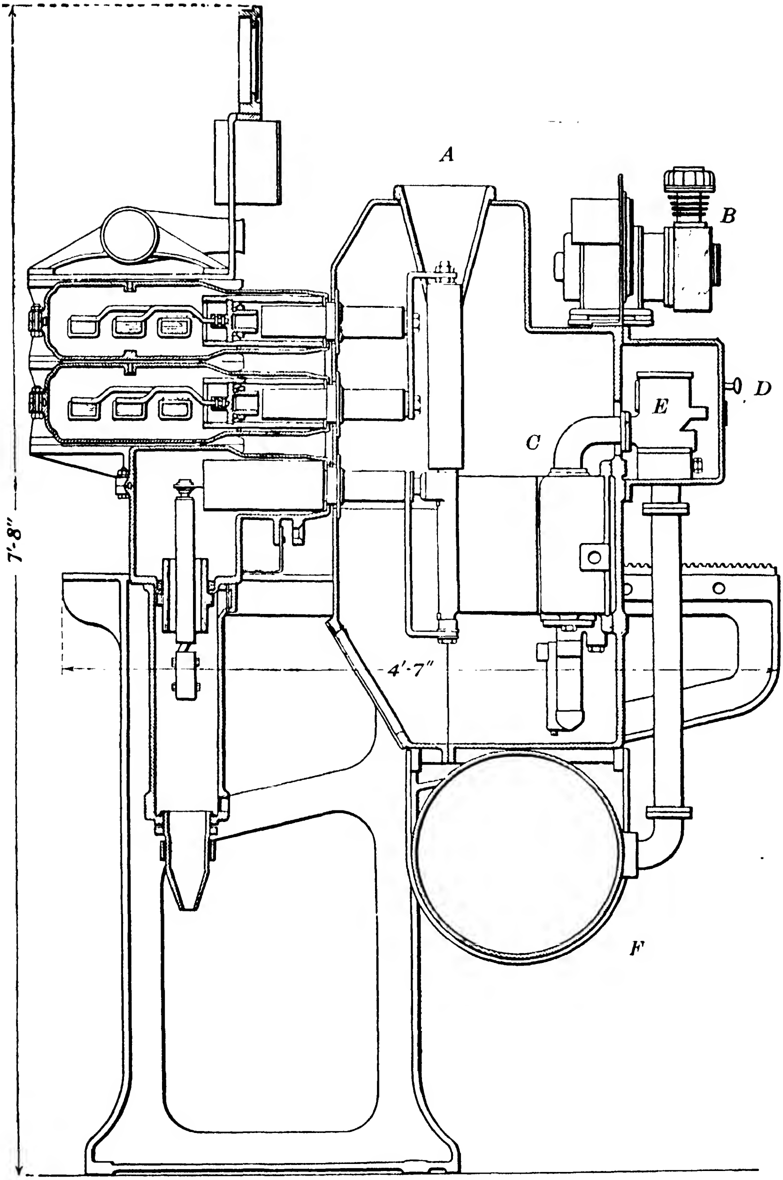


Fig. 11. Sketch Illustrating the Embodiment of an Air-blast Breaker in an Ironclad Unit

A	Air exhaust	*D*	Operating buttons
B	Motor driven air-compressor	*E*	Air valves
C	Circuit-breaker	*F*	Air tank

part of the gap between the two contacts and it will require a considerable number of half-cycles before the arc is broken. In an oil-blast or cross-jet breaker, fresh oil is moved into the arc space, and interruption will occur after a shorter time. In an oil circuit-breaker fitted with explosion pots a mixture of oil and oil gases is projected on to the moving contacts at high speed, and if the explosion pots are well-designed the result may be as good as that of an oil-blast device. The action of a water circuit-breaker is identical with that of an explosion pot, except that steam takes the place of the oil and gas mixture. In the deion-grid type of breaker the oil vapour is cooled down owing to its proximity to the walls of the slot, and fresh oil drawn from pockets in the slot is interposed. The combined action causes the arcing space to be deionized.

All the above and similar designs*—with the exception only of the oil-blast breaker with a mechanical impulse—have the common feature that their action is dependent upon the value of the current interrupted, because the speed of the deionized medium is directly or indirectly a function of the mechanical pressure set up in the arc space. Hence, all such breakers are liable to interrupt the arc more quickly at high than at low currents, and it is not uncommon for breakers which have passed tests at their rated rupturing capacity to fail when interrupting comparatively light currents.

As distinct from the above, an oil-blast circuit-breaker with a mechanical impulse (e.g. by means of a mechanically-operated piston) shows an equally good performance at any rate of current up to the rated maximum. The same applies to the air-blast breaker, which draws its deionized medium from an air tank at constant air pressure. In this type of breaker it is possible, therefore, to control the arc in such a way that interruption definitely occurs at the end of the first half-cycle of current, for any load between zero and the rated maximum.

Of course, the design of circuit-breakers clearing a circuit in so short a time as one to a few hundredths of a second, must also ensure that no undue switching surges are set up. Therefore, the current must not be interrupted before it actually passes through zero, i.e. the contact speed must not be made excessive. The performance when interrupting a light inductive load is an important criterion for the correct design of a breaker.

* For definitions, see Bibliography, No. 13.

Oilless Circuit-breakers. In the air-blast breaker the compressed air fulfils two functions, viz. it lifts the piston carrying the moving contact (*c* and *b* in Fig. 12) and also blows across

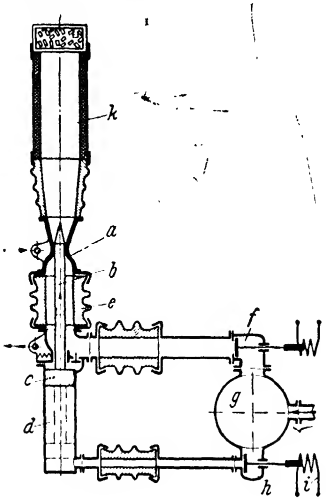


FIG. 12. PRINCIPLE OF AIR-BLAST CIRCUIT-BREAKER

a Nozzle contact
b Moving contact
c Plunger
d Cylinder
e Hollow insulator
f Trip valve
g Air tank
h Closing valve
i Closing coil
k Silencer

("*The Power Engineer*")

the contact surfaces. Both these actions only take place during the short time the breaker is operating. As may be seen from Fig. 13, there is no mechanical operating mechanism except

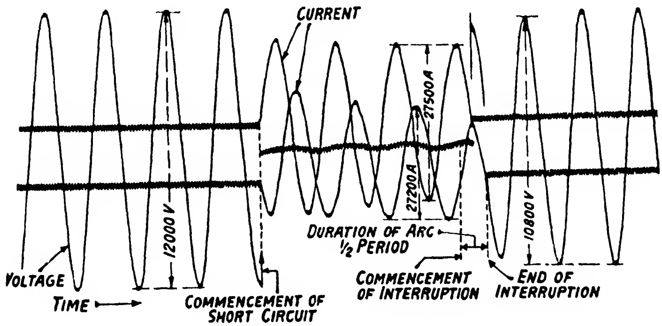


FIG. 13. TEST OSCILLOGRAM OF AIR-BLAST CIRCUIT-BREAKER

("*The Power Engineer*")

the two air valves *f* and *h* for breaking and closing respectively, which are both operated by means of small solenoids or by hand.

The quenching of the arc in an air-blast breaker is best illustrated by means of actual diagrams. Fig. 13 shows an

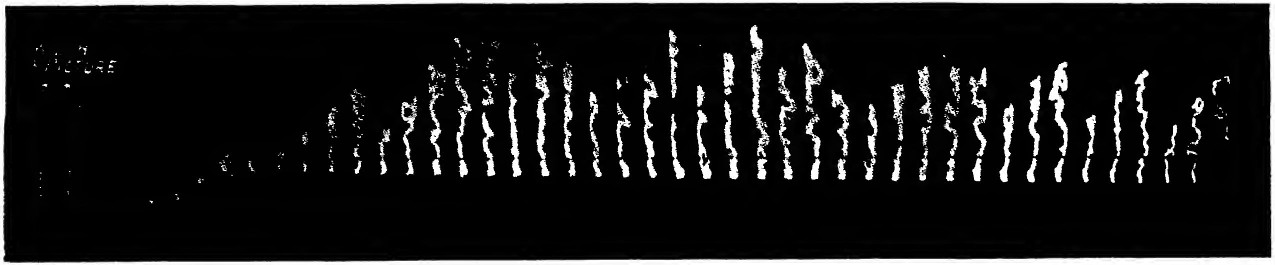


Fig. 14. High-speed Photo of Arc Interruption in an Air-blast Circuit-breaker

("*The Power Engineer*")

oscillogram taken of a breaker rated for 10 kV, 600 A, when interrupting 510 000 kVA. In this diagram it is clearly to be seen that the arc was broken within less than half-a-cycle after separation of the contacts. Still more insight is obtained from the high-speed photo reproduced in Fig. 14. In this case 5000 exposures were taken per second, so that the figure shown covers less than half-a-cycle. The arc starts as a spot of light, and by the action of the air blast it is immediately driven

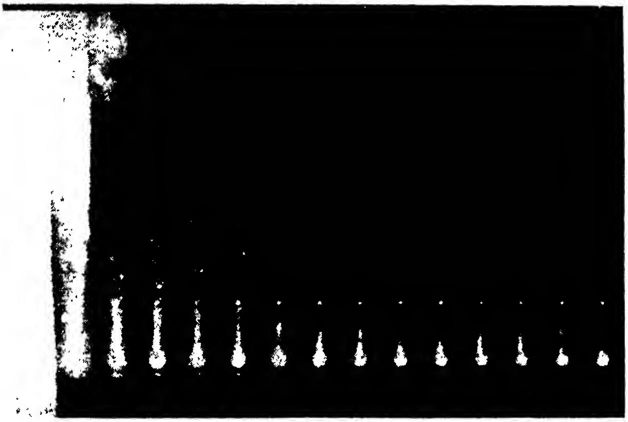


FIG. 15. THE FINAL PHASES BEFORE INTERRUPTION
(*A.E.G.*)

upwards and extended to a considerable length into the exhaust. After reaching its maximum the current (represented by the thickness of the arc) declines, until in the last picture shown the current passes through zero and the arc is finally interrupted. The final phases of interruption are again shown in another similar photograph reproduced in Fig. 15, which is from a softer print, and the fourth and fifth pictures show distinctly how the body of the interrupted arc is lifted off the pin contact and driven outwards by the action of the air blast, the space above the movable contact being filled with fresh air (appearing dark) so that re-striking is made impossible. As to the suitability of various media for the purpose of arc interruption, Table IV shows the result of tests carried out on the contacts of an air-blast breaker with various gases. It appears that the obtained rupturing capacities vary closely in accordance with the average heat conductivity of the media concerned,

between temperatures of 0 and 6000° C. abs.* Only in the case of hydrogen is the rupturing capacity markedly lower than would be expected from the high heat conductivity of this gas; this is due to the low dielectric strength of hydrogen. From the practical point of view, the fact that an arc between metallic electrodes always carries a certain amount of metal vapour must be duly taken into account.*

TABLE IV

Arc-quenching Medium	Average Heat Conductivity between 0–6000° C. Abs. referred to Air	Measured Rupturing Capacity referred to Air
Air	1	1
Nitrogen	0·8	1
Oxygen	1·8	1·8
Carbonic acid	2·5	2·6
Steam	5	3·8
Hydrogen	17	7·5

From Table IV it follows that steam has a superior quenching effect to air. This may explain the fact that much endeavour has been made to develop the water breaker in preference to the air-blast breaker. The theoretical advantage of the higher rupturing capacity of steam is, however, more than offset by the fact that in a well-designed air-blast breaker interruption invariably takes place after the first half-cycle of current, thus minimizing the energy dissipated in the arc and shortening the total inherent operating time of the circuit-breaker. Further, as yet no water circuit-breaker has been built for a voltage exceeding 30 kV. Another difficulty has been found in insulating the inside of the arcing chamber, which is necessary in view of the low resistance of water. Again, the water breaker requires a very high closing speed in order to avoid evaporation when closing. Hence a water breaker cannot be closed directly by hand, and operating devices of a special nature are necessary. Moreover, in spite of some of the water evaporated being recovered by condensation, the quantity of liquid contained is only sufficient for a very limited number of operations. Unless, therefore, recourse is had to the expedient of refilling the

* See Bibliography, No. 10.

breakers while alive, a water or expansion-type breaker must be taken out of service from time to time, and in particular immediately after the interruption of short-circuits, for refilling purposes.

The only reasoned objection to the air-blast breaker has been its inherent dependence upon a compressed-air supply and the alleged complication of the compressed-air plant. The absence of such plant was initially claimed as an advantage of

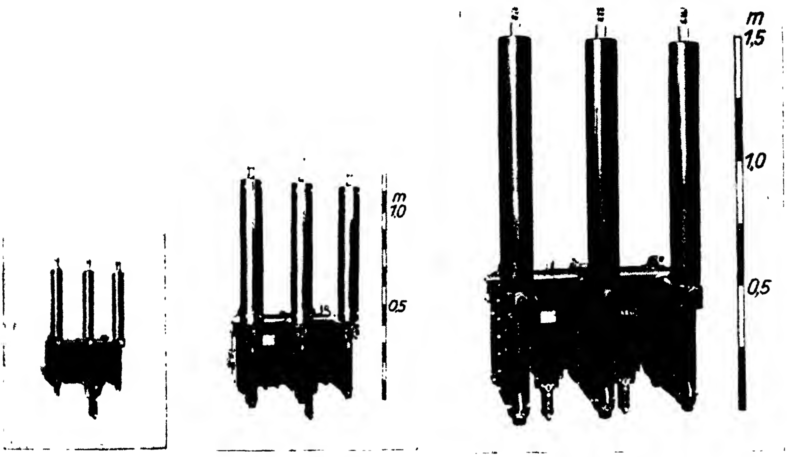


FIG. 16. AIR-BLAST CIRCUIT-BREAKERS
10–30 kV, 100–400 MVA
(*A.E.G.*)

the water circuit-breaker. In practice, however, it turned out that most of the large "Expansion" circuit-breakers built had to be fitted with pneumatic operating gear, which leads to the conclusion that the same air-compressing plant may advantageously be used not only for operating the breaker mechanism but also for quenching the arc. Careful provision must, of course, be made to ensure an uninterrupted supply of compressed air. This can easily be accomplished by means of spare compressor sets, spare air tanks, and suitable piping arrangements. Indeed, an automatic air compressor plant, with an alarm signal indicating a drop of pressure by, say, 5 per cent, is preferable from an operator's point of view to oil-breaker tanks, which, in spite of all care, may leak and eventually be half full when called upon to clear a heavy fault. Such incidents

occur quite frequently. Incidentally, it may be mentioned that the operation and maintenance of a compressed-air plant with pipes is at least as easy as that of any other known operating mechanism. The experience gained on many hundred air-blast circuit-breakers has confirmed this view.

Thus on both theoretical and practical grounds it seems fair to suggest that the air-blast principle affords the most satisfactory means yet devised for breaking high-tension circuits.

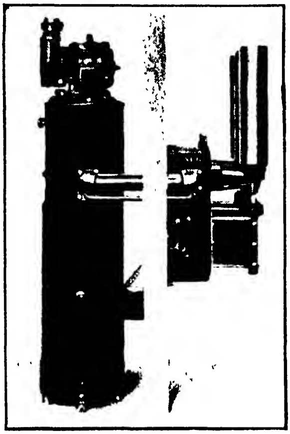


Fig. 17. Air-blast Circuit-breaker with Tank and Compressor (*A.E.G.*)

Typical Modern Circuit-breakers. For voltages up to 33 kV and currents up to 1000 A, wall-type air-blast breakers are available for rupturing capacities of 100, 200 and 400 thousand kVA, as illustrated in Figs. 16 and 17. This type is distinguished by its small dimensions and can be mounted in a vertical or horizontal position. The operating gear is separate from the breaker, which is self-contained and has silencers mounted on the top of the contacts. The weight is remarkably small, and, due to the balanced design, the breaker is free from external dynamic forces, so that this design is suitable for mounting on light walls or structures. For the smallest size, a single-stage air compressor is sufficient. Each breaker may be combined with its individual air receiver and compressor as shown in Fig. 17. In the event of several circuit-breakers being installed in one station, it is advisable

to interlink the air receivers, unless a central compressor plant and an emergency air receiver are installed for the whole plant. Figs. 18 and 19 are illustrations of typical oilless switchgear installations.

FIG. 18. TYPICAL AIR-BLAST SWITCHGEAR INSTALLATION
(*A.E.G.*)

For high rupturing capacities the appearance is somewhat different, similar designs being used for indoor and outdoor work. The somewhat higher air pressure required in this instance calls for a two-stage compressor, and as a rule it is advisable to centralize the air compressing plant of a station. The circuit-breakers for the very highest rupturing capacities and voltages are designed on similar lines; Fig. 20 shows a 66-kV model; Fig. 21 a number of 110-kV breakers installed

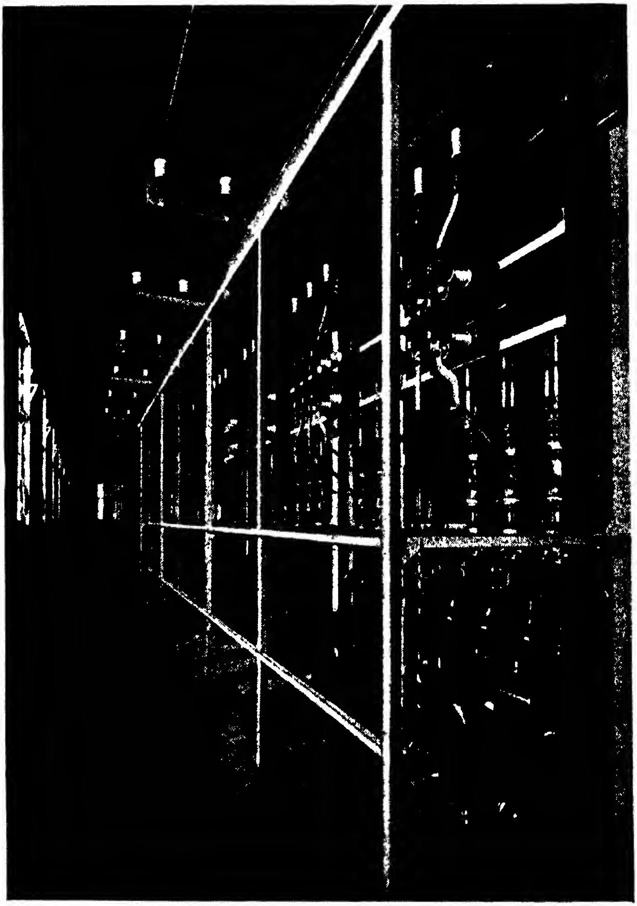


FIG. 19. 10 kV SWITCHGEAR WITH AIR-BLAST BREAKERS OF HIGH RUPTURING CAPACITY
("*The Power Engineer*")

at a hydro-electric power station; the frontispiece is an illustration of a 220-kV breaker.

On the Continent, 15 000 volts, $16\frac{2}{3}$ cycles, single-phase, is a common supply for traction purposes. For use on locomotives,

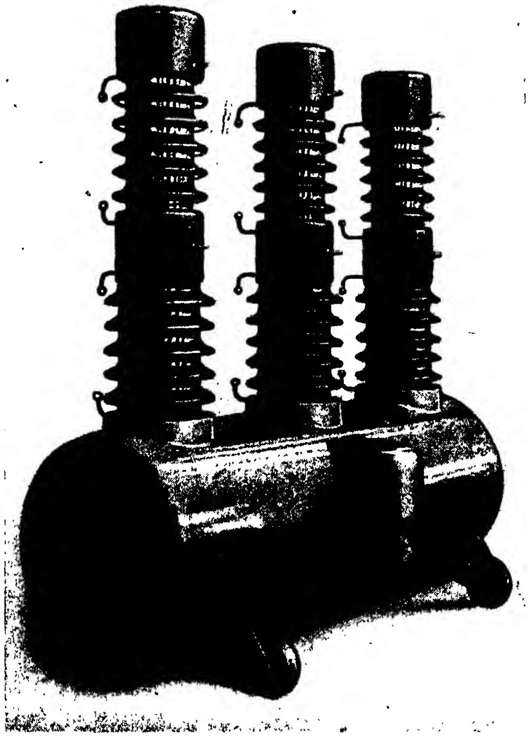


FIG. 20. 66 kV AIR-BLAST CIRCUIT-BREAKER (*A.E.G.*)

a single-pole air-blast breaker of a special type has been developed, and is illustrated in Fig. 22. Its rupturing capacity is 100 000 kVA.

Whilst all the breakers referred to above operate with an air pressure between 100 lb. for the smallest and 250 lb. for the largest size, which is sufficient to clear the arc within one half-cycle, another type has recently been built in Canada with a great number of breaks in series. This enables 100 lb. pressure

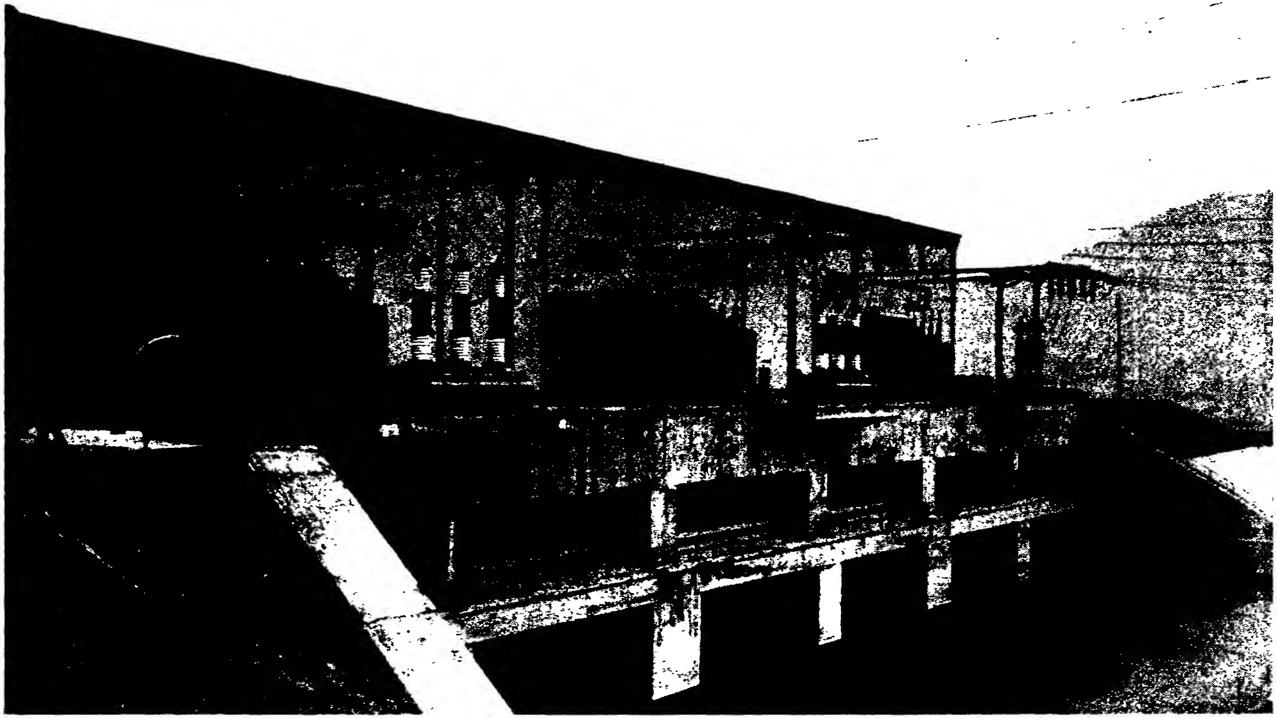


FIG. 21. AIR-BLAST CIRCUIT BREAKERS FOR 110 kV INSTALLED AT A HYDRO-ELECTRIC POWER STATION (*A.E.G.*)

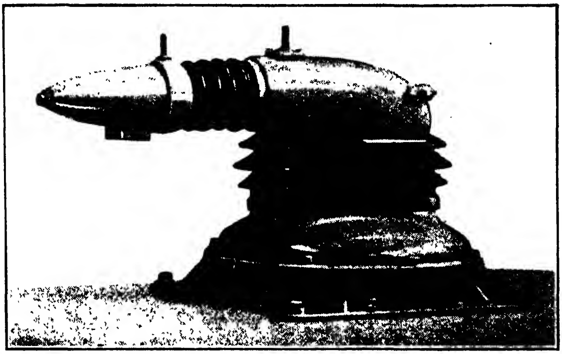


FIG. 22. 15 kV TRACTION TYPE CIRCUIT-BREAKER
("*The Power Engineer*")

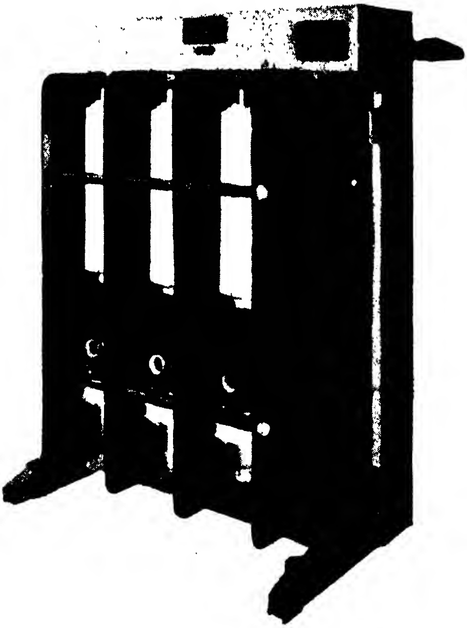


FIG. 23. 20 kV WATER CIRCUIT-BREAKER
Ferguson Pailin Ltd.)

to be used for a 132-kV breaker; the slight advantage, however, does not appear to warrant the complication of the multiple contact arrangement.

Fig. 23 shows a 20-kV water circuit-breaker with a rated normal current of 600 A and a rupturing capacity up to 250 000 kVA; Fig. 24 shows a heavier type of breaker, which can be supplied up to 22 kV for rated normal currents up to

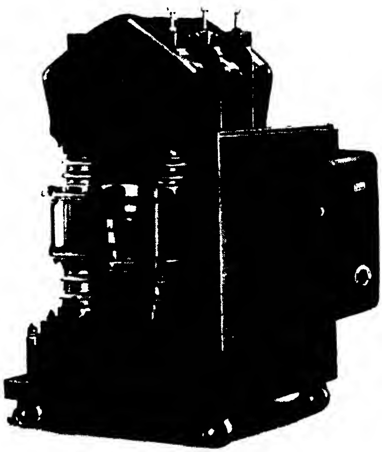


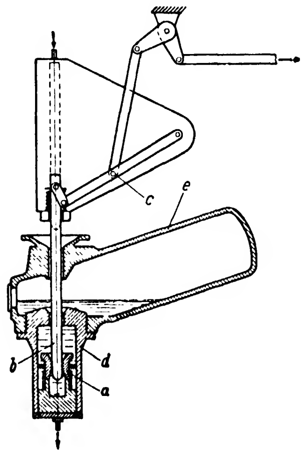
FIG. 24. 20 kV HEAVY CURRENT WATER CIRCUIT-BREAKER
(" *The Power Engineer* ")

4000 A, and a rupturing capacity of 300 000 kVA. The breaker shown in this illustration is fitted on a truck, together with a centrifugal-type operating mechanism. Fig. 25 shows a diagrammatic cross-section through a water circuit-breaker. When moved upwards, the movable contact *b*, as soon as it disengages from the fixed contact *a*, draws an arc in the water-filled arcing chamber *d*. A portion of the water is evaporated, and a steam jet blows upward after the movable contact has left the arcing chamber. The steam is subsequently condensed in the condensing chamber *e* which, in the case of the particular design represented in Fig. 25, serves at the same time as a spare water reservoir.

A Siemens-Schuckert water breaker for 10 kV, 600 A, is shown in Fig. 26, while Fig. 27 is an illustration of a large outdoor oil circuit-breaker of the "Expansion" type. A large G.E.

oil-blast or impulse circuit-breaker, with a rupturing capacity of 2 500 000 kVA at 287 kV, is illustrated in Fig. 28. Fig. 29 gives a cross-section through a 138-kV breaker of the same type.

The main operating rod, which is not shown, is connected by a clevis to a crank on the main operating shaft 1. The breaker is closed by a counter-clockwise rotation of the shaft,



a Fixed contact
b Moving contact
c Operating levers
d Arcing chamber
e Condensing chamber

FIG. 25. CROSS-SECTION THROUGH WATER CIRCUIT-BREAKER

(*A.E.G.*)

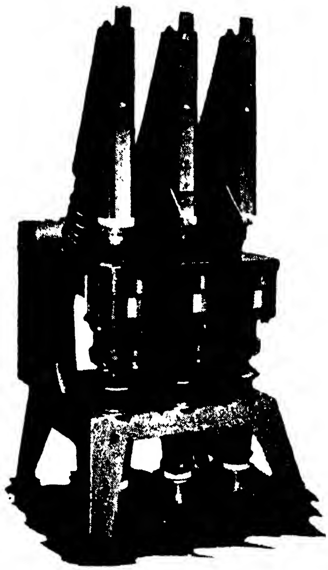


FIG. 26. "EXPANSION" TYPE WATER CIRCUIT BREAKER, 10 kV, 600 A

(*Siemens-Schuckert Werke*)

which is operated by a spring previously set by a motor and a gear train. This shaft carries two other cranks 2 and 3, Fig. 29. Crank 3 is linked to the piston 13, and lifts it up during the closing stroke, drawing up oil, through valve 12, into a pressure chamber *A*. During the closing operation, the drawing of oil from the region of the contacts is prevented by a flap valve 11. The oil returns to the centre casing, where any carbon or particles of metal from the contacts settle down. Crank 2 is linked, *via* crank 4, to two horizontal parallel operating rods 5 (shown in the smaller illustration), which, sliding on rollers, extend along the other units and carry the moving

contact 6. As the breaker is closed, these rods move inwards, i.e. to the left in the part section shown in the illustration, and engage the stationary contacts 7 and 8. The current now passes from the connection end cap to the first movable contact 6, by way of a flexible lead; then from the stationary contact 7 to the second moving contact 6, through a silver-coated joint;

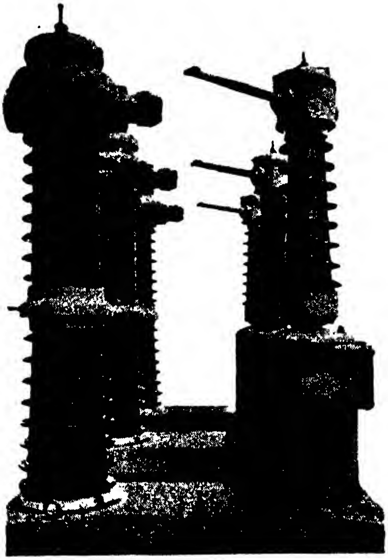


Fig. 27. Outdoor "Expansion" Type Circuit Breaker, 100 kV, 600 A
(*Siemens-Schuckert Werke*)

and finally from the stationary contact 8 through an insulated lead to a current transformer in the supporting column. A powerful spring which causes shaft 1 to rotate clockwise assures a high mechanical speed in tripping. The contacts move outwards and the piston 13 moves down. The oil closes valve 12, lifts valve 11 and passes up through ports 9 and 10. Then it traverses the path shown by a dotted line, washing the arc into these passages, and at current zero a wall of solid oil separates the ionized gases from the contact surfaces of each pair of contacts. The entire circuit-breaker has four pairs of contacts, so that a total of eight oil walls oppose re-striking of the arc.

The assembly of contacts, operating rods, etc., is mounted in a bakelite tube that supports all working parts, sustains all pressures and mechanical stresses. These bakelite tubes are protected by porcelain shells, which merely carry their own weight and hold part of the 96 gal. of oil contained in the unit. The inside of the bakelite tube is divided, slightly below the oil

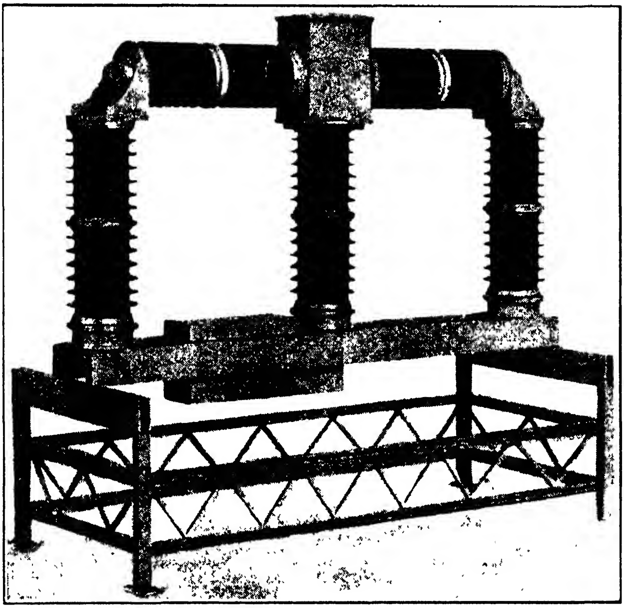


FIG. 28. 287 kV IMPULSE TYPE CIRCUIT-BREAKER
(International General Electric Co. of New York Ltd.)

level, by a horizontal diaphragm. This diaphragm separates the oil distributing manifold from the air space into which oil and gases discharge during interruption.

In this type of breaker the arc is cleared in less than two half-cycles.

Whether, ultimately, circuit-breakers will be superseded altogether by grid-controlled valves or similar devices, it is not yet possible to foretell. At present, as has been shown, the air-blast circuit-breaker appears to be the best practical solution, from every point of view, of the problem of a.c. high power interruption.

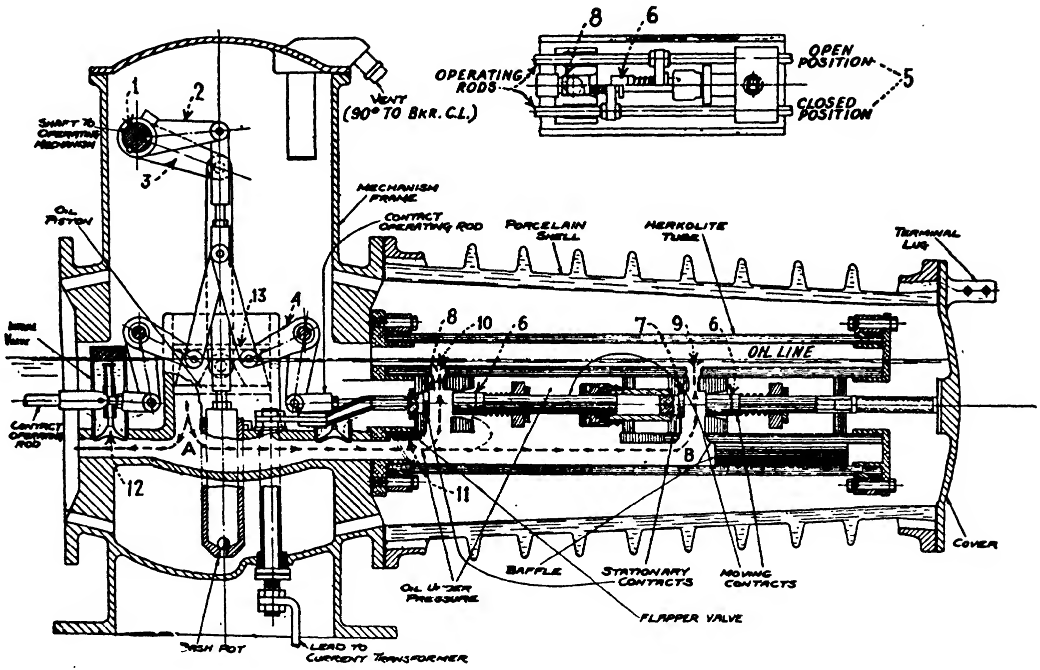


FIG. 29. CROSS-SECTION THROUGH IMPULSE-TYPE OIL CIRCUIT-BREAKER

(International General Electric Co. of New York Ltd.)

CHAPTER III

GENERATOR PROTECTION

Aim of Generator Protection. The aim of generator protection can be defined thus—

In the event of a generator being exposed to damage by any external or internal occurrence, it must be separated from the source of danger, or otherwise safeguarded in time to avoid damage, but not earlier than immediately before being liable to damage. This latter condition is perhaps the most important, and, at the same time, the most difficult to comply with. It requires the protective gear to discriminate between various types of fault, and to maintain normal operation of the protected generator for as long as is compatible with its safety. In this way other protective gear in the system is given the opportunity to act and isolate a fault or suppress a disturbance, without interrupting the continuity of generation.

A generator is exposed to damage as a result of any of the following occurrences—

Faults on Prime Movers, causing a reverse of power flow. Any type of relay having directional features gives protection against this contingency.

The use of reverse power relays is, however, not favoured in modern practice, since a reversal of power flow does not take place unless the fault is a very heavy one and even then not immediately; on the other hand, heavy fluctuations of load occur between the individual machines in the event of a temporary decrease of voltage, often causing reverse power relays to operate and cut out their alternators without need. If a reverse power relay is to be used at all, it should therefore be combined with delayed excess current protection in such a way that the time lag of the latter is reduced in the event of a power reversal.

Overspeed, causing excessive centrifugal forces and possibly a dangerous over-voltage. Suitable mechanical or electrical regulators and centrifugal switches or excess voltage relays are the means employed against this evil.

Persistent Overload causing excessive rise of temperature. As long as the temperature does not exceed the permissible limit,

it is not desirable that any automatic switching operation should be carried out (except the starting and paralleling of additional generating units in automatic stations), but an alarm should be given so that the necessary steps may be taken by the attendant. Thus overload as a danger to generators is practically eliminated, and any protective relays provided for this purpose may be regarded as a last emergency resort. In order to adapt their operation to the overload capacity of a generator, their releasing time would have to vary inversely with the current, following a curve approaching the overload time curve of the generator. This is difficult to achieve, so that relays with a definite current setting are often favoured in practice.

A fault having consequences similar to an overload is a heavy out-of-balance current due to an assymetrical load. It is considered sufficient to provide a warning signal by means of an out-of-balance relay, when the out-of-balance exceeds 10 or 20 per cent.

External Short-circuit. The effect of such faults on generators is manifold and, of course, greatly dependent on their nature. A short-circuit far away from the power station is felt more in the nature of an overload, whereas a short at or near the bus-bars imposes heavy momentary mechanical, electrical and magnetic stresses, on the windings and the iron. The momentary peak of the short-circuit current is determined by the design, notably by the leakage reactance, of a machine. It is practically the same for shorts across one, two or three phases, and seldom exceeds fifteen times the rated current with modern alternators; old machines sometimes have a momentary short-circuit current up to forty times their rated current. After a few cycles the d.c. component of the short-circuit current has disappeared, and after several seconds the a.c. component is reduced to the much lower continuous short-circuit current (see Table I). The design of modern alternators is such as to enable them to sustain a short-circuit across their terminals without mechanical or magnetic damage. Hence, the permissible duration of the short is, again, as in the case of overload, only determined by the temperature of the windings, and the same relay is, therefore, used for dealing with both types of fault. The permissible duration of the short-circuit determines the definite minimum time setting of the excess current relay. Under normal circumstances the time setting is between 4 and 7 seconds.

Internal Short-circuits. In contrast to external faults, these necessitate instantaneous disconnection of the faulty generator from the bus-bars. The conventional type of protection is a *differential circulating current* relay of the Merz-Price type. A variety working on a similar principle is the Beard (self-balancing) system. The latter has the disadvantage that it is

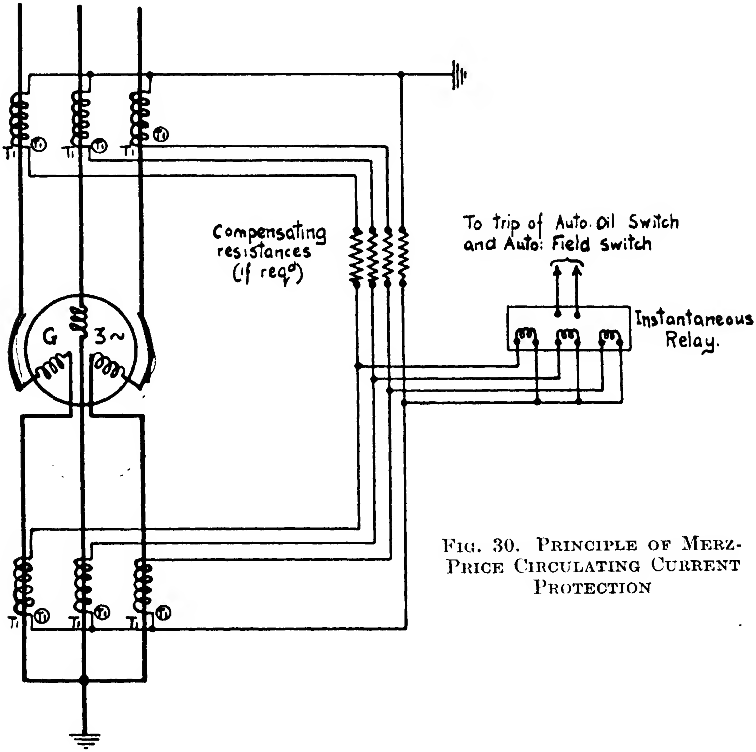


FIG. 30. PRINCIPLE OF MERZ-PRICE CIRCULATING CURRENT PROTECTION

difficult to build self-balance current transformers with adequate insulation and dynamical strength. Both systems originated in England and have found widespread application in all countries. Out of numerous modifications some important improvements will be of interest.

If the circulating current system is applied in its original form (Fig. 30), the two sets of current transformers must, of course, be accurately balanced; further, in order to balance the burden it is necessary to connect other (e.g. excess current)

relays and instruments to separate current transformers, and further to insert compensating resistances. Without these precautions, excessive currents may pass through the relays in the event of faults outside the protective range, and undesired relay operation would ensue.

In the conventional type of differential relay the current

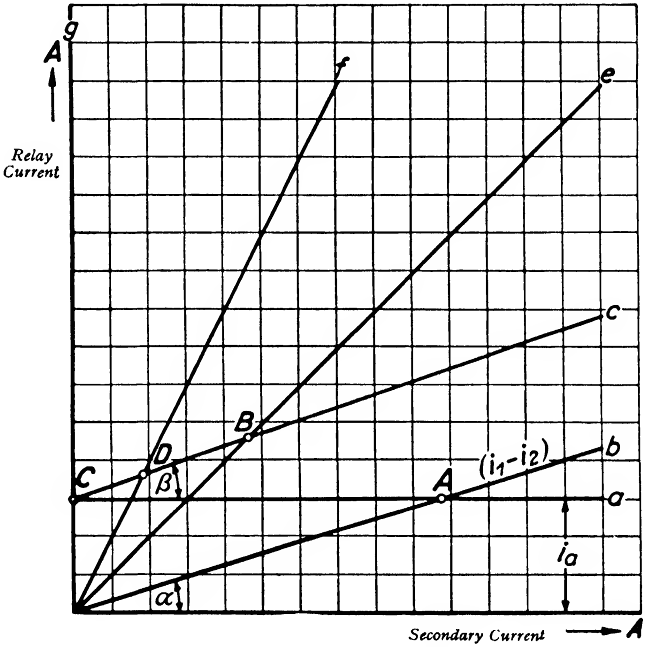


FIG. 31. PERFORMANCE OF DIFFERENTIAL RELAYS IN UNBALANCED CIRCUITS

setting is determined by the constant force of a weight or spring (line *a* in Fig. 31). If the error current due to a slight unbalance in the current transformers or leads is plotted in the same diagram (line *b*), it will be seen that the line representing this error current is inclined. Any secondary current to the right of the intersection (*A*) of the two lines *a* and *b* causes an undesired relay operation. The obvious remedy is to make the counter-force in the relay dependent on the alternator current, as indicated by line *c*. This is achieved by the addition of a biasing restraint coil (*H* in Fig. 32).

The angle α is small as long as a short-circuit is outside the relay range; if, however, a fault occurs within the relay range, i.e. between the two sets of current transformers, the out-of-balance current is heavy and angle α is almost 90° (lines *e*, *f* or *g*).

Differential relays provided with a restraining coil may be connected to ordinary bushing transformers. Thus a fundamental disadvantage of the original circulating current system has been eliminated. A typical modern three-phase electromagnetic differential relay built on these lines is illustrated in Fig. 33. There are two systems working against each

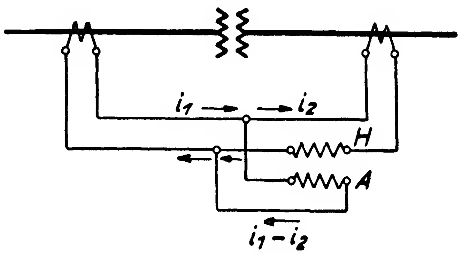


FIG. 32. CIRCULATING-CURRENT PROTECTION WITH MCCOLL RESTRAINT COIL

A—Tripping coil. *H*—Restraint coil.

other; the top system carries the fault current or error current $i_1 - i_2$ (Fig. 32), whereas the bottom (restraining) system is energized by the operating current i_2.

Any scheme of alternator protection should, as a rule, be combined with a quick-acting field-weakening device. The relay contacts are also often used for closing the main steam valve and for operating fire extinguishers.

In Fig. 34, which illustrates a typical example of modern protective gear for a medium size alternator, a CO_2 type of fire extinguisher is operated also in case of an earth fault. This provision has been made for the reason that no direct protection is installed against faults between turns (a rare occurrence); it is safe to assume that a leakage between turns is accompanied by an earth fault.

A separate set of current transformers must be used for the connection of excess current, reverse power and earth leakage relays and measuring instruments, unless a special design of combined differential and summation transformers (*K*, *M*, *D*

in Fig. 34) is utilized. These combined current transformers are of the self-balancing type. The two ends of each alternator phase winding are brought out, and passed through a common iron circuit. The secondary differential and earth leakage winding *D* (Fig. 34) consists of several parts suitably distributed over the iron core. The core is bridged across the

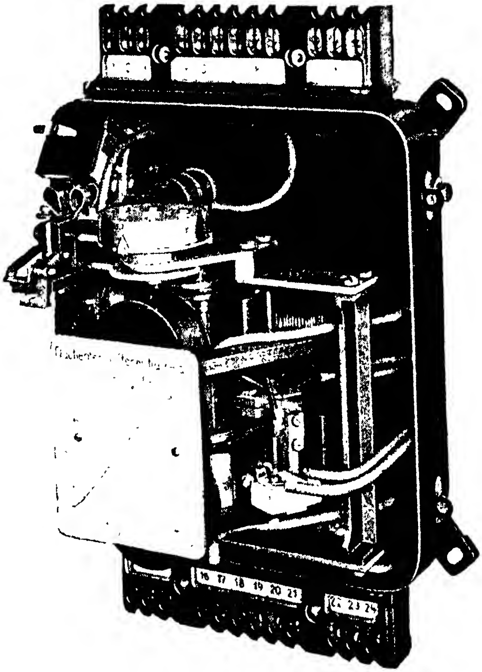


FIG. 33. MODERN DIFFERENTIAL RELAY
(*A.E.G.*)

centre; the flux in this centre leg corresponds to the sum of the two primary currents. The centre leg carries a secondary current winding *M*, to which the excess current and reverse-power relays are connected.

The application of *distance relays* to alternator protection might be considered in plant of minor importance. These relays are able to replace not only the differential relays, but also the excess current and reverse power relays. Thus the protective equipment of a generating unit can be greatly simplified, in particular if, instead of three distance relays in the three

phases, only one is used together with suitable change-over relays.

As distance relays are mainly applied for the protection of ring main feeders and interconnected networks, they will be dealt with in greater detail under that heading (see Chapter VII). Normally, the distance relays are provided with directional features. For generator protection, the relay (or

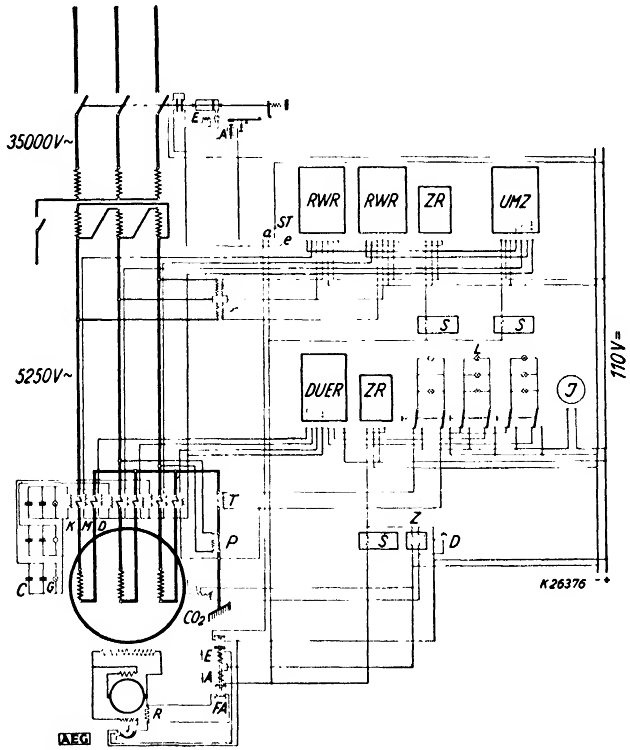


FIG. 34. EXAMPLE OF PROTECTIVE EQUIPMENT FOR A MEDIUM SIZE ALTERNATOR

DUER	Differential and earth leakage relay	*P*	Assymetry transformer
K,M,D	Combined differential and summation current transformers	*R*	Resistance
C	Condensers	*RWR*	Reverse power relay
G	Glow lamps	*S*	Flag indicator
FA	Field weakening equipment	*ST*	Control switch
A	"Off" coil	*T*	Transformer
E	"On" coil	*UMZ*	Definite-time excess-current relay
D	Push button	*Z*	Intermediate relay
I	Ammeter	*ZR*	Time relay
L	Iron resistance lamps	*a*	"Off" contact
		e	"On" contact

(*A.E.G.*)

relays) should be non-directional, so as to act in the event of any internal or external overload or short within the alternator circuit (including the bus-bars), even if the protected alternator is the only one in operation.

External Earth Faults. If the alternator forms part of a system protected by a Petersen coil (see Chapter VI), no further earth protection is required; but an indicating relay is usually installed so as to enable the position of the fault to be ascertained without delay. This indicating relay is of the wattmeter type, and is connected to the common earth lead of three current transformer secondaries and to a neutral potential transformer. Normally, both the resulting current and the neutral potential are nil, while, in the event of a fault to earth, the relay operates a signal.

Internal Earth Faults can be dealt with by similar earth relays.

The determination of the correct size and method of connections of the *neutral resistances* is a matter of some complexity.* On the one hand, a neutral resistance should be connected to the star-point of each alternator, of a resistance value sufficiently low to keep the neutral potential down when an earth fault occurs, and to admit a fault current not too low for the operation of earth relays; on the other hand, it is desirable to keep the earth current as low as possible, so as to prevent damage to the machines, and to avoid an earth fault developing into a multi-phase short. In a station containing a number of alternators, each having its own neutral resistance, the value of the earth current in case of a fault varies in accordance with the number of units actually connected to the bus-bars. It is therefore often advisable to install an artificial neutral transformer, connected directly to the bus-bars, and to connect the only earthing resistance to the star point of this transformer. These are conflicting conditions, but if the problem they present is approached intelligently, it will be found possible to satisfy the several major requirements in any given case, and at the same time to leave some degree of latitude in the choice of the correct size and arrangement of the earth resistances. In many cases the use of voltage-dependent iron filament resistances will be found to be advantageous.†

A typical example of modern protective gear incorporating iron resistances for a medium size alternator is illustrated in Fig. 34. Nine iron lamp resistances L are connected to a

* See Bibliography, No. 20. † See Bibliography, No. 19.

potential transformer T, three of them in series with the earth relay. Due to their characteristics, these lamps normally have a low resistance, and are thus effective in leading to earth an excess voltage on the alternator winding. On the other hand, the current from an earth fault in the alternator circuit is quickly reduced to a very low value by the increasing resistance of the lamps as they heat up. With this arrangement, it is safely permissible to continue operation with one phase earthed until another machine has been started up. The second potential transformer P serves to displace the neutral potential, so that operation of the earth relay is secured even when the fault is at, or near, the star-point of the winding.

Multiple Earth Faults. As far as alternators are concerned, this type of fault is practically identical with short-circuits.

Faults between Turns. The timely detection of this class of fault may avert heavy damage. On the other hand, the means available for this purpose are rather complicated and are not, therefore, always provided. As already mentioned, faults between turns are almost invariably accompanied by simultaneous earth leakage, so that protective gear acting in case of internal earth faults may be looked upon as a sufficient safeguard. The most successful system of direct protection against faults between turns consists of a reactance or potential transformer connected in parallel with each phase winding of the alternator, and with midpoint tappings in both. The respective midpoint tappings of the phase windings and the parallel reactances are connected through an auxiliary current transformer, which is energized in case of any internal unbalance, and operates the tripping circuit.

Excess voltage. As regards surges due to atmospheric discharges, switching operations, or persistent arcs, it is not necessary to provide separate protection for an alternator, since excess voltage arresters installed at each outgoing feeder or on the bus-bars* are sufficient protection for the complete station including the alternators.

If a small alternator is connected to a step-up transformer, a puncture fuse may be fitted in order to prevent damage to the alternator in the event of the machine becoming connected to the h.t. side as a consequence of a transformer fault.

Under-voltage, Instability. It has been shown above that perfect protection of an alternator may be achieved either by

* See Chapter V.

means of excess current relays of the inverse definite minimum time lag type, combined with differential current relays and an earth relay of the wattmeter type, or alternatively, by means of distance relays combined with an earth relay. In both cases a reduction of the continuous short-circuit current has often been attempted by means of quick-acting field weakening gear. This measure results in a depression of the terminal voltage, and is, therefore, liable to interfere with the co-operation of several power stations feeding into a common network. Except perhaps in the case of isolated power stations, it is desirable to *maintain* the voltage and thus prevent any alternators or whole power stations from falling out of step; thus, a tendency is advocated in certain quarters not to weaken, but to *strengthen* the fields of alternators in the event of external short circuits.* Where any part of the system is unable to sustain the full (or even increased) short-circuit currents due to this measure, the subdivision of bus-bars, with or without reactors between the sections, offers a simple and reliable remedy (see Chapter V).

* See Bibliography, No. 1.

CHAPTER IV

TRANSFORMER PROTECTION

Aim of Transformer Protection. The aim of transformer protection is similar to that of alternator protection. As in the case of alternators, the protection must be effective against external and internal faults.

External Faults and Overload. The effect of external (terminal) faults is kept away from a transformer by means of excess current relays, or better still, by circulating current protection. Of course, the latter requires current transformers with equal *secondary* currents on both sides. Special overload relays have also been developed, acting on the square of the current in excess of normal. Alternatively, contact thermometers are suitable for the same purpose.

Internal Faults—Differential Protection. As a protection against internal faults, including leakage between turns, the original circulating current method is not sufficiently sensitive. The magnetizing current and the alteration of ratio by tappings or induction regulators, introduce well-known difficulties. An improvement was effected through the use of biased relays, such as are referred to in Chapter III.* In view of the initial current surge when connecting a transformer to the supply, a time relay must be added. If the protected transformer is combined with a tap-changer or induction regulator, it is always advisable to insert an equalizing transformer as shown in Fig. 35. A system according to this diagram is also suitable for the protection of a transformer with a Petersen coil† connected to its star-point.

Good results have also been obtained by means of ordinary differential relays, each with a separate locking relay, whose contact is connected in series with that of the circulating current relay; these locking relays prevent tripping due to external short-circuits without impairing sensitive action on internal faults.‡ The locking relays may be equipped with change-over contacts and, in conjunction with a time relay,

* See p. 42 and Figs. 32–33; also Bibliography, No. 30.

† See Chapter VI.

‡ See Bibliography, No. 29.

be used for delayed tripping in the event of external short-circuits.

Very sensitive protection may be obtained by the introduction of wattmeter-type relays. Through this system it is possible to separate the copper and iron losses, and to use only the latter for discrimination. Thus, the relay only responds to changes of flux or to faults in the windings. This arrangement

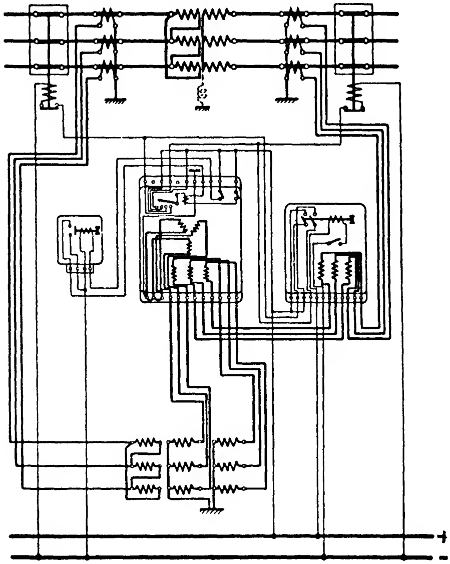


FIG. 35. DIFFERENTIAL TRANSFORMER PROTECTION (*A.E.G.*)

is shown in Fig. 36 as applied to a transformer connected in star/star. An auxiliary transformer (*DH*) supplies to the current coils of the wattmeter relay (*WDR*) the difference of the currents on both sides. The voltage coils of the relay are energized through a potential transformer. The equipment will operate if the losses are only 2 per cent in excess of normal. A scale on the relay indicates the magnitude of the iron loss.

This equipment is, however, unnecessarily elaborate and expensive, and for these reasons little applied in modern practice. Another solution giving satisfactory results is protection by means of distance relays. The connections in this instance are the same as for ring main feeders (see Chapter VII).

But these, again, are not much used, as there is another more direct means of transformer protection in respect of all internal faults, viz. the Buchholz relay.

The Buchholz Relay. This device is extremely simple and reliable. It consists of a small tank inserted in the pipe connection between the transformer tank and its conservator. Normally, the relay is filled with oil and a float arranged

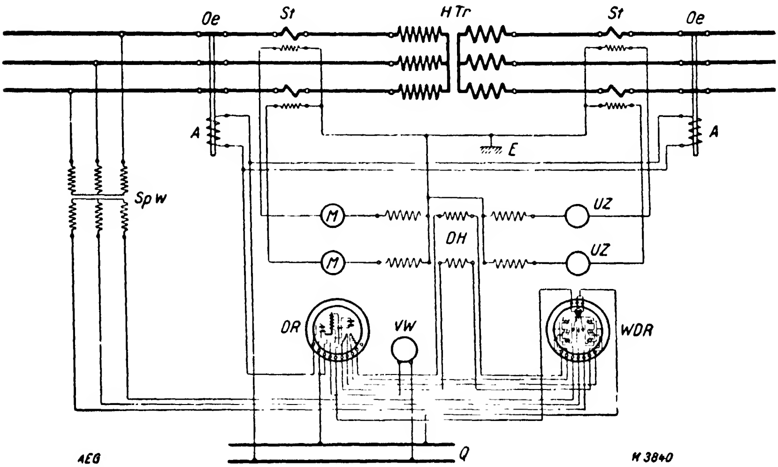


Fig. 36. Differential Protection Using Wattmeter Relay (*A.E.G.*)

A	Releasing coil of circuit-breaker	*Q*	Releasing current source
DH	Auxiliary transformer	*SpW*	Potential transformer
DR	Differential relay	*St*	Current transformer
HTr	Main transformer	*UZ*	Overload time relay
M	Measuring instruments	*VW*	Series resistance
Oe	Circuit-breaker	*WDR*	Wattmeter differential relay

therein is pressed upwards. In the event of a fault, gas bubbles rise instantaneously, and on their way upwards are trapped in the relay, whose upper part quickly fills with gas. The float drops with the oil level and operates a mercury switch in the tripping or alarm circuit. In order to make the operation definite in any case, a ball is provided inside the float which rolls down and forces the float into the bottom position. It is also possible to use two floats (Fig. 37); in this case the upper one becomes operative in the event of a very light fault, and is used for operating an alarm. When the fault persists, or becomes more serious, the second contact eventually closes and causes tripping

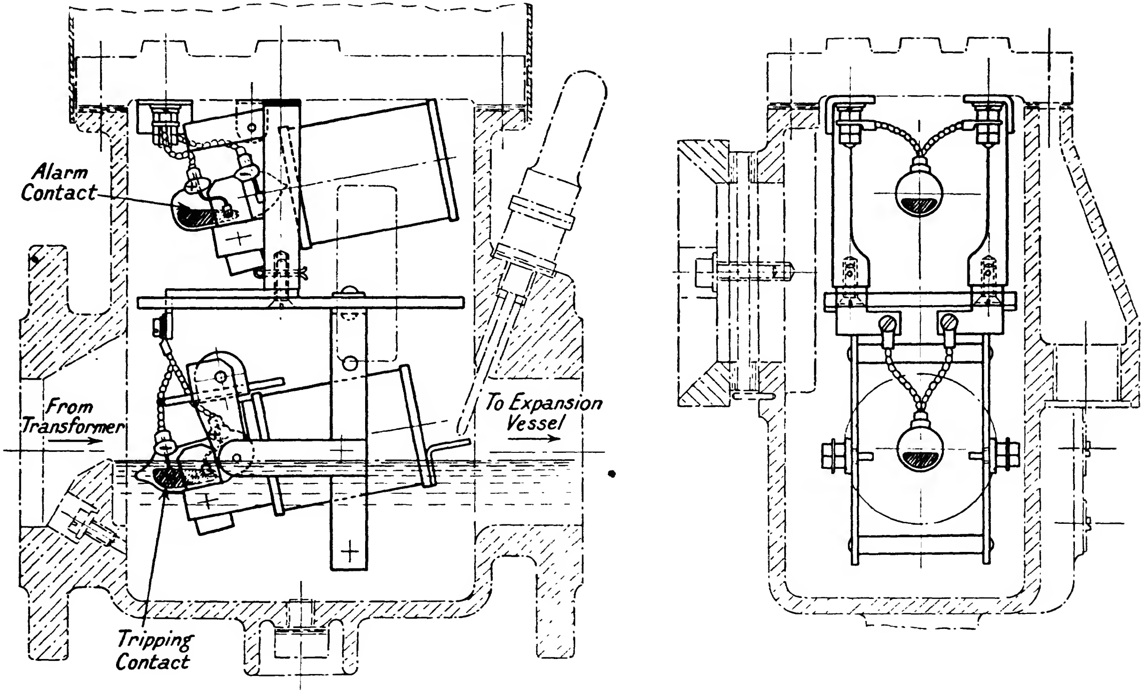


FIG. 37. CROSS SECTION THROUGH BUCHHOLZ RELAY
(A.E.G.)

of the circuit-breaker. Fig. 38 shows a transformer equipped with a Buchholz relay.

The Buchholz relay is much employed with transformers of

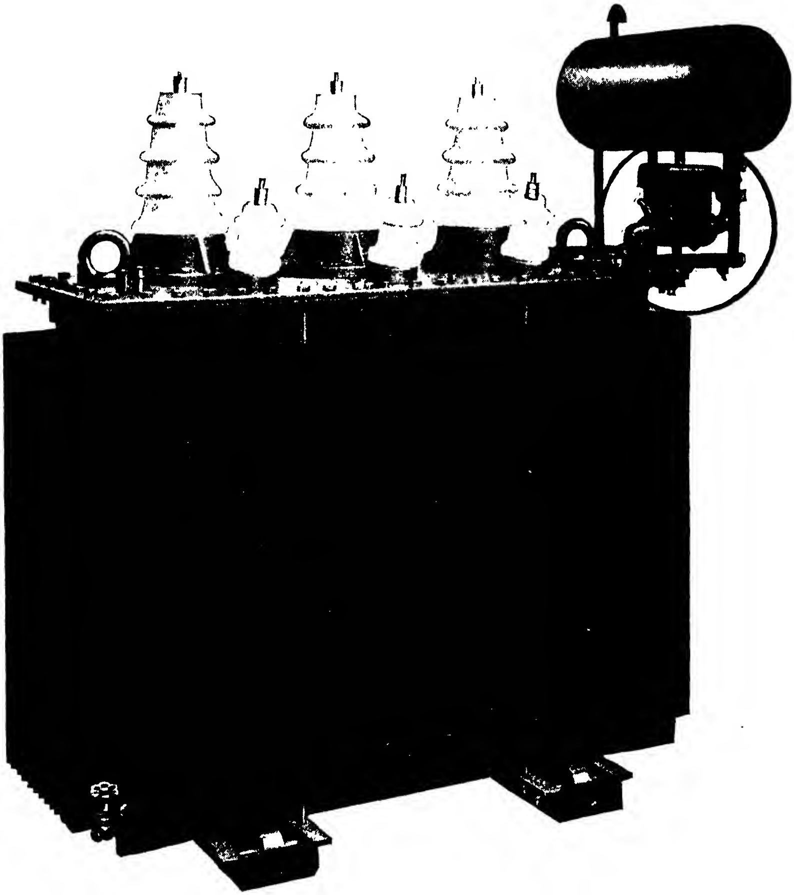


FIG. 38. TRANSFORMER EQUIPPED WITH BUCHHOLZ RELAY (*A.E.G.*)

every size and description. It requires only the addition of excess current, distance, or differential relays with high setting, or of a contact thermometer, to provide against overload and faults at the terminals and in the external connections.

For small distribution transformers, in connection with solidly interconnected l.t. networks (see Chapter VIII), no external

short-circuit protection need be installed, as the maximum current is limited by special reactors on the l.t. side. The protective gear of such transformers is thus limited to a Buchholz relay and a contact thermometer, both operating the h.t. circuit-breaker and the l.t. reverse power breaker. If indication of internal faults is considered sufficient, the h.t. circuit-breaker may be omitted (see Fig. 132).

Earth Faults. No separate protection from earth faults is required in systems protected by a Petersen coil, but a signalling relay should be installed as in the case of alternators. If automatic disconnection is required, e.g. in the case of transformers feeding underground cable systems, this may be achieved by differential relays or by means of wattmeter-type leakage relays. In systems with solidly earthed neutral, a leakage relay may be connected to a current transformer in the earthing lead, or earth protection may be combined with excess current, distance, or differential protection.

Excess Voltage. Separate surge protection for transformers is not required. Suitable excess voltage arresters installed at the bus-bars of a station (see Chapter V) will extend protection to all transformers in the same station. It may be pointed out, in this connection, that recent research has established beyond all doubt the fact that the most important factor endangering modern transformer windings is not the steepness of the front, but the peak value of a surge.* The protective value of surge arresters is much improved by interconnecting their earth leads with the secondary (l.t.) transformer neutral.

In cases where a great number of small distribution transformers, each protected by quick-acting fuses, are arranged along a feeder, a frequent form of disturbance due to atmospheric excess voltages is the blowing of a number of fuses. As this mainly applies to outlying rural districts, considerable delay occurs in replacing the fuses and restoring the supply. The cost of protecting each transformer by a separate set of arresters may be found to be prohibitive. In such cases it is useful to remember that a very high percentage of lightning trouble is not caused by the voltage surge itself, but by power current which follows through the highly ionized path prepared by a flash-over. For this reason it is possible to obtain a satisfactory degree of safety by installing a reduced number of arresters on points of special importance, and by

* See Bibliography, No. 74.

earthing the system neutral through a Petersen coil. The latter will suppress the following power current entirely, and thereby prevent the blowing of fuses.

Windings of booster transformers are particularly exposed to damage by excess voltage surges, and it is therefore recommended to protect them by means of shunt-connected arresters (see p. 61).

CHAPTER V

PROTECTION OF BUS-BARS AND SWITCHGEAR

Current Limiting Devices. Though circuit-breakers are themselves installed mainly for the protection of other plant, they also must be afforded protection from being stressed beyond their own rupturing capacity. If the short-circuit currents which may occur are in excess of those for which switchgear (including bus-bars, current transformers, etc.) is designed, it would be subjected to excessive mechanical stresses, and possibly also to overheat. Should this be the case, the maximum short-circuit currents must be reduced. This may be achieved either by means of current limiting devices or by subdividing the bus-bars into individual sections; between sections current limiting *reactors* may be inserted. These are, as a rule, of the cast-in-concrete design, which is most suitable for dealing with the high mechanical stresses imposed by a short-circuit. A typical current-limiting reactor is illustrated in Fig. 43. Besides protecting the main switchgear from being overstressed, these reactors also have a second and equally important function, viz. to localize a heavy voltage drop, as is necessarily incidental to heavy faults, and to prevent the falling out of synchronism of all machines connected to the same bus-bars.

Since reactors are permanently in circuit, their reactive value is limited through considerations of working under normal conditions. This can be avoided, and higher reactance values can be employed, if an arrangement as in Fig. 44* is used. The main reactor winding (1) is, in this case, opposed and its reactance neutralized by a second winding (2) which is cut out in the event of a heavy fault through a fuse or valve (3). A third winding (4) is available for auxiliary, e.g. alarm purposes.

Current limiting reactors of whatever type are exposed to damage by excess voltage surges, and should be shunted by suitable excess voltage arresters (see p. 61).

Another modern method of limiting the short-circuit current makes use of quick-acting high power *fuses* which interrupt

* Brit. Patent No. 421467 (Mackay and Knowles).

the current long before the highest peak is reached. A successful quick acting h.t. fuse is illustrated in Fig. 39. The fuse

Fig. 39. Carbon Tetrachloride Fuse
(*Allen West*)

element consists of two wires, one a strain wire of high resistance material, and the other the fuse element proper. When the fuse operates, the spring is released, and the arc is quickly drawn into the liquid and extinguished; on heavy shorts, a vent cap is blown off, thus relieving the pressure.

Another type, operating without any moving parts and without liquid filling, is shown in Fig. 40. In this case, one or several silver wires are wound on a ceramic carrier and surrounded by sand. When a short-circuit or heavy overload occurs the wire evaporates, and forms with the surrounding sand a semi-conductive tube (Fig. 41), the resistance of which depends on the temperature and becomes infinite when the temperature is sufficiently low. Actually, the convection of heat is sufficient to reduce the temperature, once all metal has been evaporated, i.e. from approximately one-tenth of a cycle after the inception of a short-circuit. Thus this type

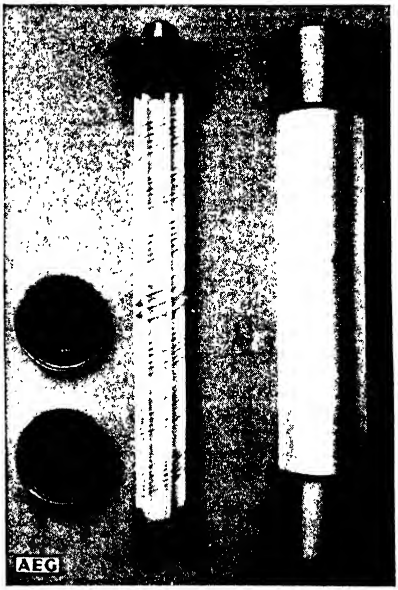


Fig. 40. H.S. Type High Power Fuse Cartridge. Three-phase Rupturing Capacity, 400 MVA
(*A.E.G.*)

FIG. 41. FUSE-WIRE CARRIER AFTER OPERATION ON A SHORT CIRCUIT

Showing the compound formed from the sand surrounding the evaporated silver wire

(A.E.G.)

of fuse prevents the short-circuit current from reaching its full peak value, and interrupts the circuit in less than one-half cycle without a rupturing arc and thus entirely noiseless. The three-phase rupturing capacity is 400 000 kVA.

The usual tell-tale

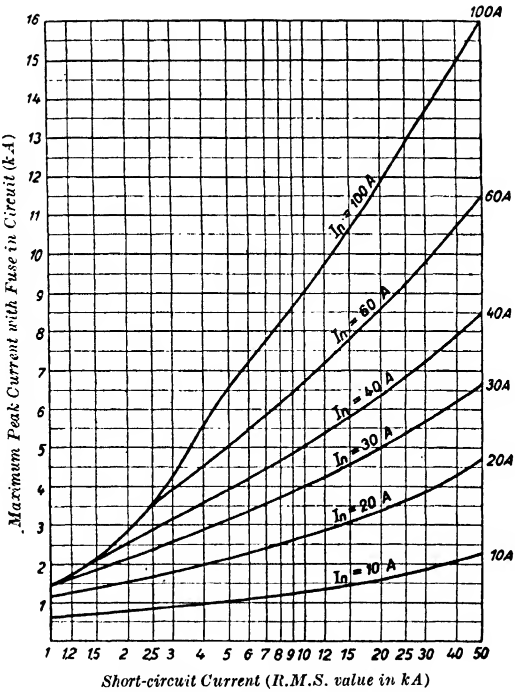


FIG. 42. CHARACTERISTICS OF H.S. TYPE HIGH POWER FUSES (FIG. 40), SHOWING THE CURRENT LIMITING EFFECT

I_n = Rated current of fuse

(A.E.G.)

wire may be carried through a small explosive cartridge which drives a small plunger out of one end; this may be used for tripping a switch, thus effecting isolation of all three phases. The current limiting effect of such high power fuses (which are now available for voltages between 3 and 33 kV and all current ratings occurring in normal practice) is evident from the curves given in Fig. 42.

Short-circuits across the bus-bars themselves are more frequent occurrences than is often assumed. At the same time they are among the most feared, since they lead to the disconnection of all feeders connected up to the station involved. It is, therefore, recommended to separate the three phases throughout, in open or cellular switchgear by suitable barriers, and in metalclad gear by compound insulation. Where this measure is economically feasible, a bus-bar short is made a very rare event.

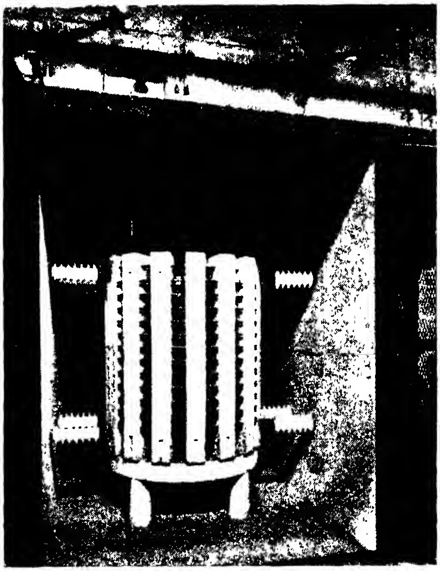


Fig. 43. Cast in Concrete Type Current Limiting Reactor
(B.T.-H. Co. Ltd.)

Excess current or distance relays and the latest types of directional balance protection afford protection from bus-bar short-circuits by the relays installed for the protection of transformers and feeders, so that no additional bus-bar protective relays are required in conjunction with these systems.

Split-conductor, differential or older directional balance systems, however, leave the bus-bars unprotected and require supplementary bus-bar protective gear. Circulating current systems are suitable for this purpose, but their cost and additional complication are sometimes considered prohibitive. As a rule it is necessary to install three extra current transformers

in each feeder, since the existing current transformers are usually rated in accordance with the load on their respective feeders. The difficulty of providing adequate bus-bar protection is an important point against the use of differential systems of feeder protection.

Excess Voltage. Electrical apparatus installed in stations, particularly in those connected to overhead transmission lines, is exposed to excess voltages, due to lightning or other sources.

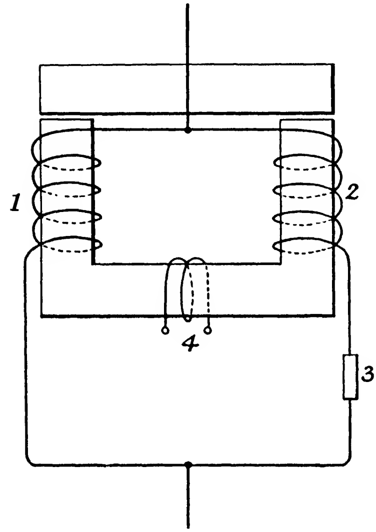


FIG. 44. COMPENSATED CURRENT-LIMITING REACTOR
(*Hackbridge El. Constr. Co.*)

In the next chapter it will be shown that even without the employment of special line protective devices, excess voltages reach a station in the shape of a surge having a crest value of, say, ten times the rated r.m.s. voltage, which may rise to about twenty times the rated voltage by reflection. On lines supported by wooden poles, the crest value of surges may rise up to 500 kV, independent of the nominal line voltage. Excess voltage surges travel along the line with almost the velocity of light and have often steep fronts with a rise of possibly 300 kV per microsecond, which corresponds to 1 kV per yard. The total time of the front may vary between 1 and 10 microseconds (corresponding to a length of 300 yd. to 3000 yd.); after reaching the crest the voltage drops comparatively slowly; normally, after 5 to 50 microseconds half the crest value is reached again.

Protection against surges must be afforded to bus-bars, and to all switchgear, transformers and machines connected thereto. In switching stations, protection may be achieved by raising the "level of insulation"* above that of line insulation, a measure often impracticable, and as a rule not advisable. The normal and indeed logical practice, is to provide the unprotected line with a higher, and station equipment with a lower level

* See Bibliography, No. 58.

of insulation, the latter being efficiently protected by suitable excess voltage arresters. In end stations excess voltage protection is required under all circumstances, in view of the further increase of voltage due to surge reflection. In through-stations, the amount of voltage increment due to partial reflection depends on the number of outgoing feeders.

In principle there are two distinct ways of combating excess voltage surges, viz: dischargers or arresters, and absorbers.

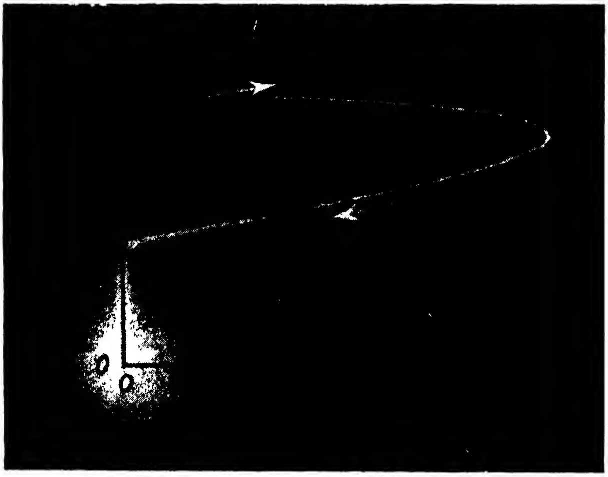


FIG. 45. VOLTAGE/CURRENT CHARACTERISTIC OF AN AUTO-VALVE ARRESTER

(*a*) EXCESS VOLTAGE ARRESTERS, connected between each phase and earth, and consisting of a resistance element in series with a spark gap. The spark gap flashes over when the line potential exceeds a certain value (usually at twice the rated voltage). The resistance should be as low as possible under excess voltage, so as to allow instantaneous discharge to earth. As soon as the line voltage returns to normal the flow of current through the arrester must stop, i.e. re-ignition must be averted. A high resistance is now desired, in order to facilitate interruption.

The oldest type of excess voltage arrester known was a horn gap with a ceramic or water resistance. This design, however, did not comply with any of the requirements stipulated above, and was, therefore, wholly inadequate. In theory, better results

can be obtained with aluminium cells or oxyde film arresters. Aluminium arresters, however, require careful and tedious attention and both types have been found to cause a certain amount of trouble, sometimes even endangering the plant which they were supposed to protect.

A more practical solution is offered by the auto-valve arrester and related types. This consists of a column of discs

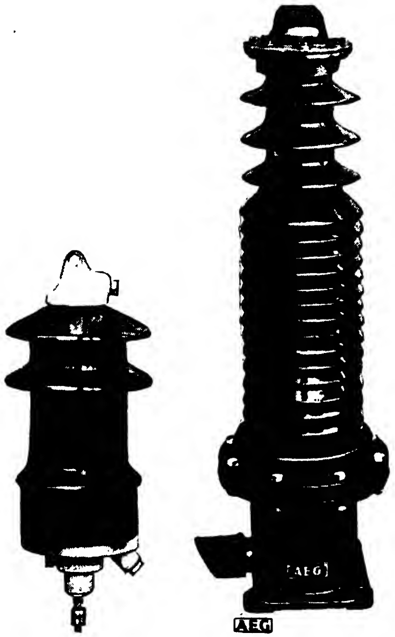
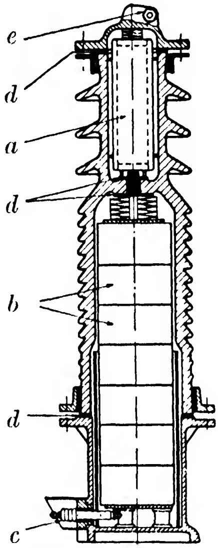


FIG. 46. OUTDOOR SURGE ARRESTERS FOR 11 AND 33 kV (*A.E.G.*)



a Multiple spark gap
b Voltage-dependent resistance discs
c Earth terminal
d Sealing
e Line terminal

FIG. 47. CROSS-SECTION THROUGH 33 kV S.A.W. ARRESTER (*A.E.G.*)

with gaps between them, or of a porous block. In the gaps or pores a gaseous discharge occurs when the space is sufficiently ionized due to a high potential being applied. This type of arrester complies with all the above conditions but one: the operation is not instantaneous. At least one microsecond (millionth of a second) is required for the ionization preceding the discharge. This delay may be detrimental, as the fronts of surges are often so steep that the peak voltage is reached

within 1 or 2 microseconds, i.e. before the arrester becomes operative.

This time lag is clearly visible in the oscillogram (Fig. 45), where the two curves, corresponding to rising and dropping voltage, form a loop.

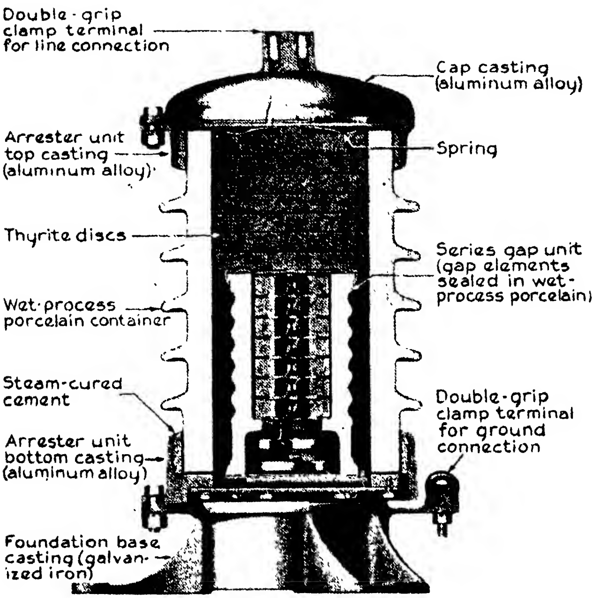


FIG. 48. CROSS-SECTION THROUGH 11·5-KV. THYRITE ARRESTER
(*International General Electric Co. of New York Ltd.*)

The most successful type of arrester, according to the author's experience, is the "Thyrite" or "S.A.W." type. This consists of a compound material whose resistance varies inversely with the third or fourth power of the voltage applied to its terminals,* connected in series with a multi-spark gap. The normal setting of the spark gap is such that the discharge through the arrester starts at twice normal line voltage. For the highest voltages this would not be satisfactory, and the action of the spark gap is then controlled by a number of shunt resistances, with the effect that the initial discharge voltage under impulse

* See Equation 4*a* in Chapter I.

conditions becomes substantially lower than that on operating frequency.

Fig. 46 shows typical outdoor arresters for 11 kV and 33 kV, and Fig. 47 a cross-section through one of them. Fig. 48 is another design based on the same principle. Fig. 49 illustrates the effect the arrester has on a surge with high peak and steep front. It will be seen that the crest value of 580 kV is reduced

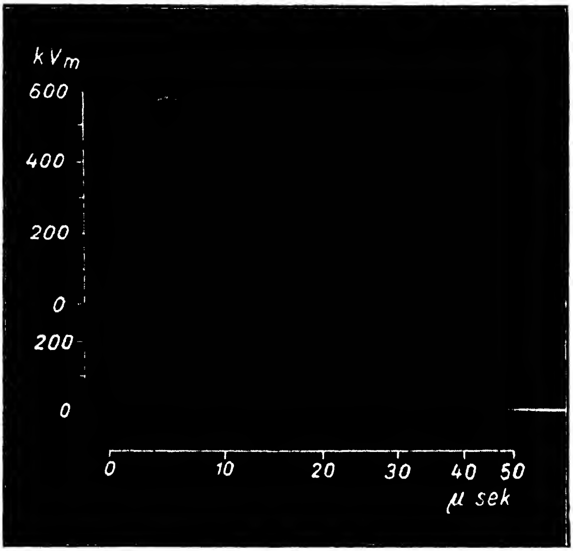


FIG. 49. SURGES ON A 30 KV SYSTEM, WITH AND WITHOUT ARRESTERS IN CIRCUIT

(*A.E.G.*)

by the action of the arrester to 90 kV, which is well below the surge flash-over voltage of transformers or switchgear of a 30-kV system, on which this oscillograph was taken. The action of this arrester is positive on any type of excess voltage, including surges of any shape. The time lag is less than 10^{-7} sec., i.e. the operation is practically instantaneous. Accordingly, the two lines of rising and dropping voltage in the oscillogram (Fig. 50) coincide, and there is no loop.

Arresters of this design are available for any voltage up to 220 kV, for installation indoors or outdoors. It has been established by extensive field tests with the use of surge generators, that normally it is sufficient to connect one set of arresters

to the bus-bars of each station for the mutual protection of all gear connected to the same. It is essential that the leads between bus-bars (or conductors) and arresters, as well as between these and earth, should be as short as possible. Frequently a discharge counter is connected in the earth lead of each arrester or of each set of arresters. Since the discharge to earth lasts too short a time for operating a counter mech-

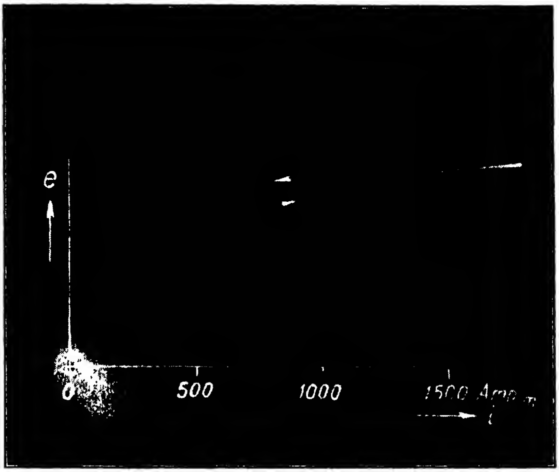


FIG. 50. VOLTAGE/CURRENT CHARACTERISTIC OF S.A.W. ARRESTER
(*A.E.G.*)

anism, it is only used for discharging a small condenser which is subsequently charged up from a dry battery (Fig. 51). The charging current performs the operation of the counter mechanism.

The action of surge arresters can be slightly improved by connecting two or three of them in parallel, or by adding a shunt condenser. As a rule, however, this is unnecessary.

(*b*) SURGE ABSORBERS, i.e. apparatus connected in the line circuit with a view to absorbing the energy of a surge while it is passing through, may either be static condensers connected between each phase and earth, or choking coils connected in the run of a line. Both expedients may also be combined. Condensers have found little use in practice, in view of the high cost.

The widespread practice of using pieces of underground cable between bus-bars and an overhead feeder, is an application of this type of protection. It is effective to a certain extent, but owing to the practical impossibility of using cables of sufficient length, the protective value is mostly inadequate against protracted surges. It is advisable to use cables insulated for a higher than the system voltage.

Choking coils have also been frequently installed for the

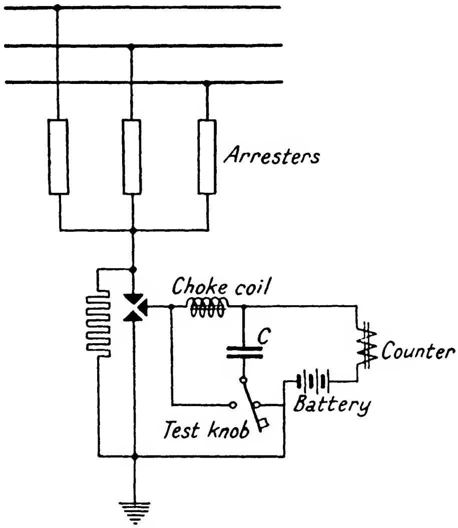


FIG. 51. CONNECTION OF THREE ARRESTERS WITH DISCHARGE COUNTER

purpose of surge protection. Their shunting by resistances of "Thyrite" or "S.A.W." material is a useful improvement. For obvious reasons, the inductance of such coils must be kept comparatively low, so that the flattening effect on a surge is very small, unless a steeper wave front is applied than those actually occurring in practice. Even then, the peak voltage is not sufficiently reduced, as may be seen from test results published.* Hence, a choking coil of practicable dimensions cannot have any substantial protective value. It has been contended that the effect is improved through a distributed capacitance to earth (*surge absorber*, see Fig. 52), but that contention has been submitted to criticism which appears to

* See Bibliography, No. 68 (Fig. 41).

be well substantiated.* It seems only to be justified when the inductance of the coil is as low as about 1000 μH, but even then the combined effect of the coil and the earth capacity, including the additional effect due to dielectric discharge and eddy currents in the shell forming the secondary circuit, is considerably less than that of an ordinary choking coil, for

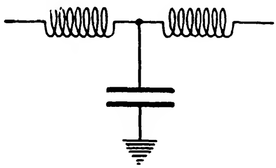


FIG. 52. DIAGRAM OF SURGE ABSORBER

instance of the "Campos" type, a device much used in the past with an inductance over 5000 μH.

DIRECT STROKES OF LIGHTNING. All means of surge protection enumerated above are designed with a view to reducing the shape and size of incoming surges to harmless dimensions, but not to afford protection from direct strokes of lightning into the station itself, or into a line in the immediate neighbourhood; though there is much evidence suggesting that up-to-date excess voltage arresters are suitable for dealing with such an emergency. In any case, stations themselves should be built in such a way as to prevent a direct stroke reaching the apparatus. This is achieved by overhead earth wires or masts shielding the station area, and by the installation of earth wires, or in the event of wooden pole lines, expulsion protective gaps† on the adjoining line sections.

* See Bibliography, Nos. 52, 54, 60.
† See Chapter VI.

CHAPTER VI

H.T. FEEDER PROTECTION

THE choice of protective gear is, of course, influenced by the construction of the feeder itself. Partly different gear may be used for underground cables or for overhead lines; the importance of a feeder, the operating voltage, the number of sub-stations connected, and the availability of alternative means of supply, are other factors influencing the choice of protective equipment.

Earthing of the Neutral. A fundamental question is the method of earthing the neutral. In favour of *solid earthing* can be claimed the absence of substantial excess voltages due to an arc to earth, and further, the fact that there can be no rise of the star-point potential in the event of an earth fault; hence, the insulation of transformer windings may be of the "graded" design, whereby the cost of transformers is substantially reduced, and the well-known "shielded" type of windings may be applied. On the other hand, earth currents are very high if the neutral is earthed solidly, and every earth fault is a single-phase short and leads to an interruption of supply.

By earthing the neutral through a *resistance*, the magnitude of earth currents can be limited. As in the case of solid grounding, the line must be isolated immediately when an earth fault occurs. Altogether, results with the neutral earthed through a resistance have not proved too satisfactory.

The Petersen Coil. If the one advantage of using transformers with graded insulation is relinquished, then the problem of earthing the neutral can be solved in an ideal manner by means of the Petersen arc suppressing coil or equivalent device. This principle is illustrated in Fig. 53. In the event of a fault to earth on an unprotected line with insulated neutral, the fault (which may be either in the nature of a solid contact or, more frequently, of an arc) carries a leading current. This current is composed of the two charging currents of the healthy conductors, i.e.

$$I_{RC} = 2\pi f \times C_R \times V_{BR} \quad . \quad . \quad . \quad . \quad (5)$$

and

$$I_{YC} = 2\pi f \times C_Y \times V_{BY} \quad . \quad . \quad . \quad . \quad (5a)$$

where f denotes the frequency, C_R and C_Y the capacitance to earth of each conductor, and V_{BR} and V_{BY} the acting line voltages, each equal in magnitude to $V_{ph} \times \sqrt{3}$.

The resulting fault current

$$I_E = I_{RC} \hat{+} I_{YC} = 2\pi f \times (\sqrt{3})C_{ph} \times (\sqrt{3})V_{ph}^{*} \quad (6)$$

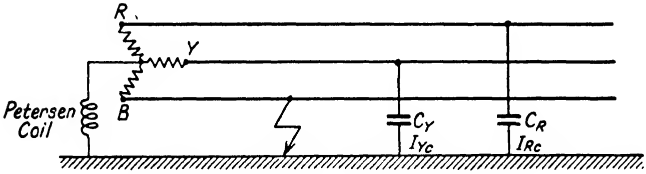


FIG. 53. PRINCIPLE OF PETERSEN COIL

C_R, C_Y = Earth capacities

I_{Rc}, I_{Yc} = Currents to earth

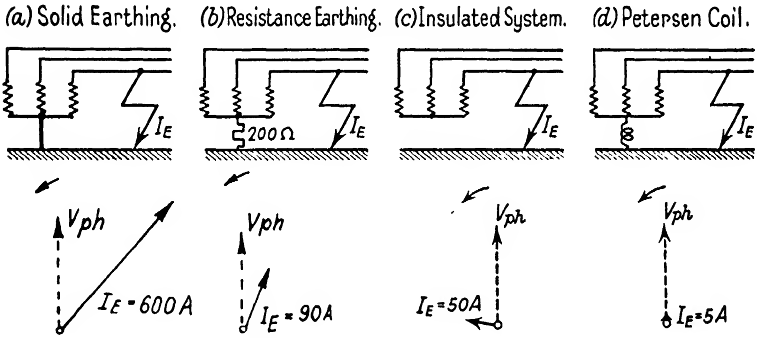


FIG. 54. EFFECT OF NEUTRAL EARTHING ON CURRENT THROUGH A FAULT TO EARTH

I_E Current through the fault

if sufficiently large, maintains an arc to earth, whereby serious damage may be done before the fault is isolated. As a rule this applies when the leading fault current exceeds about 3–4 A.

If, now, as shown in Fig. 53, a choking coil (Petersen coil) is inserted between the star-point of a transformer (or alternator) winding and earth, of such inductance L_p that the lagging current in the circuit composed of the phase winding B of the transformer (or alternator), the coil, and the fault,

$$I_{Bi} = V_{ph}/(2\pi f \times L_p) \quad . \quad . \quad . \quad . \quad (7)$$

* The symbols $\hat{+}$ and $\hat{-}$ are used to indicate a "vectorial sum" or "vectorial difference."

is equal to the leading earth current I_E, the resulting current through the fault will be nil, apart from the very small watt component due to the ohmic resistance of the circuit. This follows from the fact that the phase of I_{Ei} is 180° different from that of I_E. Thus, no arc can be maintained, and a single-phase earth fault does not cause interruption of service, if

$$L_p = 1/[(2\pi f)^2 \times 3C_{ph}] \quad (8)$$

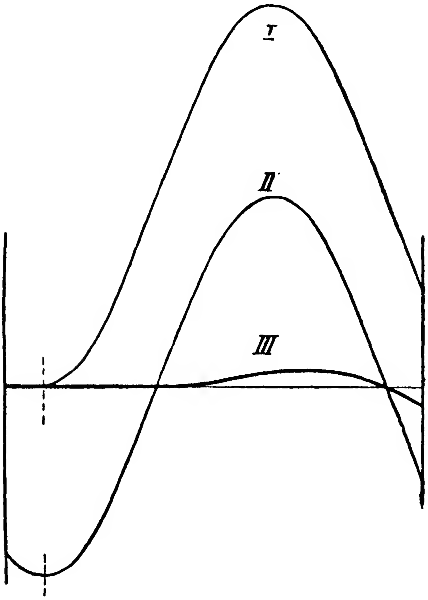


FIG. 55. CONDITIONS FOR THE MAINTENANCE OF AN ARC TO EARTH (A.E.G.)

I—Voltage rise with fully insulated neutral
II—Normal phase voltage
III—Voltage across the fault with Petersen coil in circuit

Fig. 54 compares the effect of various methods of earthing the neutral. The conditions assumed are those of a typical 33-kV network having a total extension of 100 miles. In the case of solid earthing, the current through the fault depends upon the distance of the fault from the supply end, and is here assumed to be 600 A; it is lagging behind the voltage of the faulty phase. An earth resistance reduces the fault current, but at the same time displaces the current vector considerably. In the case of fully insulated neutral, the current leads by nearly 90° and amounts to, say, 50 A. With a Petersen coil, the residual watt component will not exceed 5 A.

The duration of the arc is determined by the fault current and by the conditions prevailing between the arc terminals. On an unprotected system, the voltage across the arc (Curve I in Fig. 55) rises to twice the normal voltage (Curve II) during the first cycle. A Petersen coil suppresses the voltage to a small residual value (Curve III) and thus prevents restriking. On the other hand, after extinction of the arc, current continues to oscillate in the circuit composed of the coil inductance

and the line capacitance, with the natural frequency of this circuit.

As may be seen from Fig. 56 (taken on a 110-kV line), this natural oscillation decreases gradually, while the voltage between the faulty phase and earth shows a simultaneous slow increase back to normal. At the same time, the potential of the two healthy phases also returns to normal.

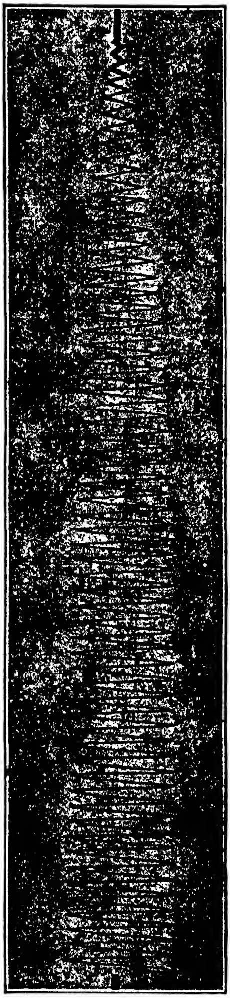


FIG. 56. CURRENT OSCILLATION THROUGH PETERSEN COIL AND LINE CAPACITANCE
This oscillation is essential in order to obtain the arc suppressing effect
(A.E.G.)

Thus, the great majority of earth faults are reduced to a short "kick," and will, as a rule, remain almost unnoticed. Due to the slow and gradual return to normal conditions, no over-voltage can be set up. The comparatively rare occurrence of a solid contact between one phase and earth, e.g. by a broken conductor, is also dealt with by the Petersen coil, and operation may be continued with one conductor earthed, for such a length of time until the affected section can be isolated for repair. It is, therefore, recommended to design Petersen coils for continuous rating.

The great value of the Petersen coil is confirmed by its commercial success. It is in use on over 1000 systems, comprising about 200 000 miles of overhead and underground h.t. lines in all parts of the world, with voltages between 6 kV and 220 kV. In Europe, with the exception of this country, there are not many h.t. lines without the protection of a Petersen coil. On all these systems earth faults, formerly the main cause of interruptions, ceased to be regarded as a serious disturbance; the total number of interruptions was thereby greatly reduced; in addition, much damage was averted and, in

several instances, men making contact with a conductor under full operating voltage, owe their lives to the compensating effect of a Petersen coil. Interference with telephone circuits is also greatly reduced by these coils.

On overhead lines, the coil is still fully effective when out of tuning by as much as 10 to 25 per cent. The lower value refers to very high, the higher to medium voltages. A number of tappings are provided in order to adapt the coil inductance to the capacitance of variable lengths of lines.

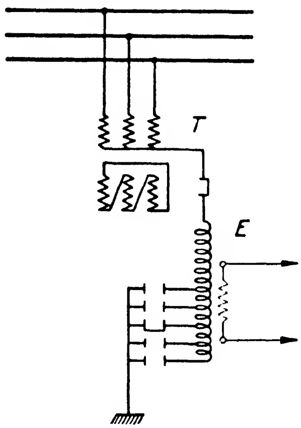


FIG. 57. NORMAL CONNECTION OF PETERSEN COIL

(*A.E.G.*)

T Power transformer
E Petersen coil

Fig. 57 illustrates the principle of connection.

The design of a Petersen coil is similar to that of a single-phase transformer. Fig. 58 illustrates a large outdoor coil for use on a 220-kV system. The construction of the core is shown in Fig. 59. As will be noticed, its legs are divided by a number of gaps. The winding (Fig. 60) is constructed like a transformer winding, and insulated for the line voltage.

As will be clear from what has been said above, the Petersen coil as a means of eliminating the great majority of line interruptions is the most important component of protective gear as a whole. It is therefore appropriate to analyse in greater detail one of the objections sometimes brought forward against its use, i.e. the alleged creation of dangerous over-voltages.*

The Petersen arc suppressing coil is most efficacious when its inductance and the earth capacitance of the network under protection combine to produce a natural electrical frequency that is equal to the normal working frequency. Therefore, that which is otherwise viewed with trepidation in high-tension technique is particularly aimed at in this instance; namely, an oscillatory circuit of widest possible range that embraces the entire network and is just in resonance with the working frequency of the network. Hence, as the voltage

* The following analysis is taken from Bibliography No. 21, by kind permission of Professor J. Biermanns.

to earth of the neutral point of the network which is caused by unsymmetrical line capacitances or by external influences need not necessarily be zero, the possibility of deleterious resonance phenomena occurring cannot be denied from the outset. On

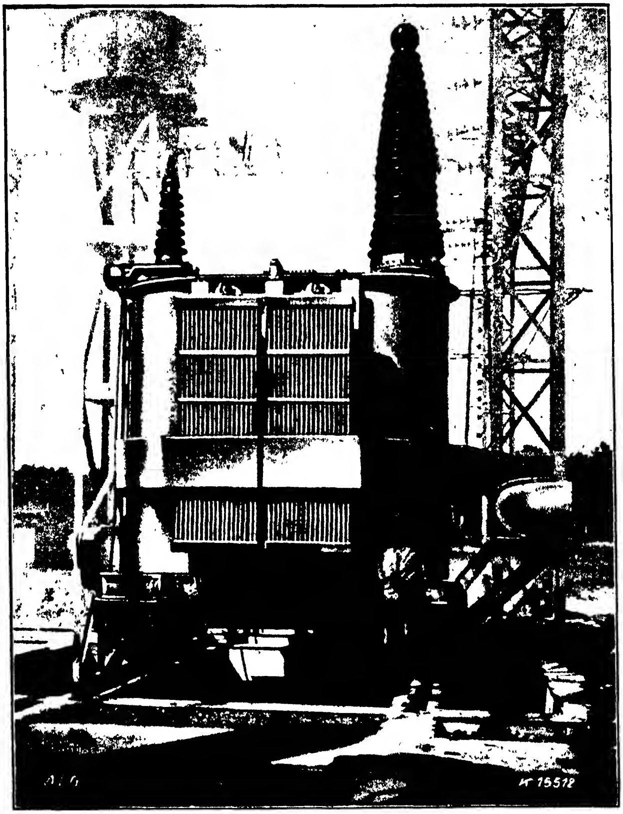


Fig. 58. Large Petersen Coil for 220 kV
(*A.E.G.*)

the contrary, it is imperative to provide ways and means which will definitely prevent the development of dangerous over-voltages due to resonance.

The required effect is, however, inherent. The arc suppressing coil embodies a magnetic path which is for the major part closed, and like in every such apparatus, the normal point

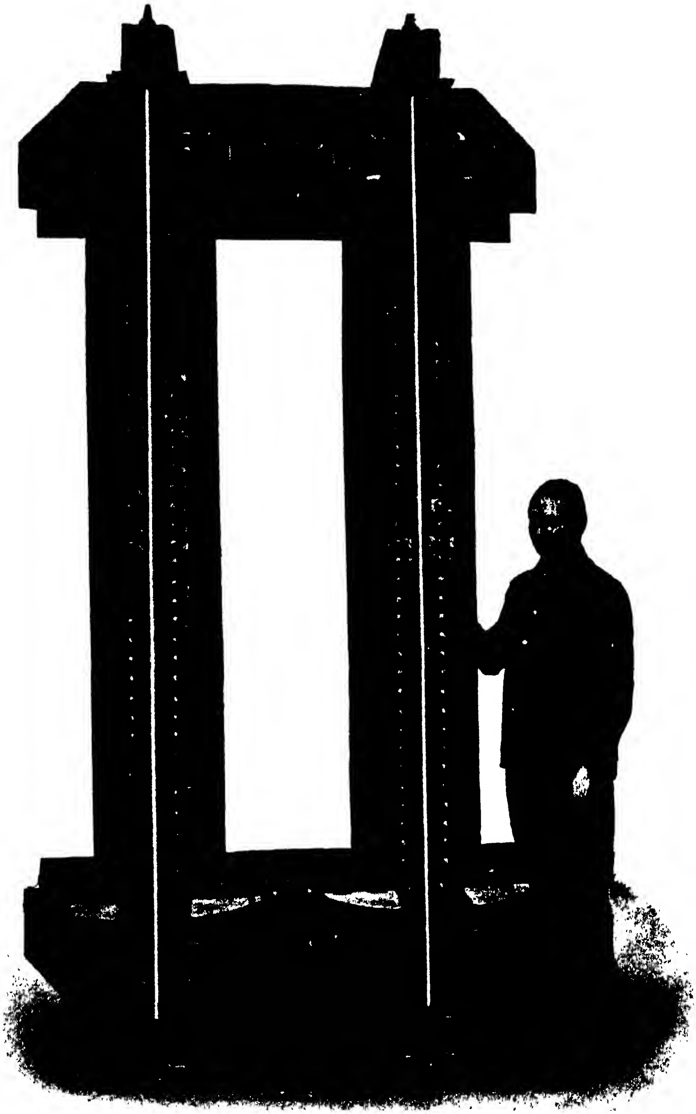


Fig. 59. Core of Large Petersen Coil
(A.E.G.)

of saturation of the iron core is also selected of such value, for economic reasons, as is compatible with other technical

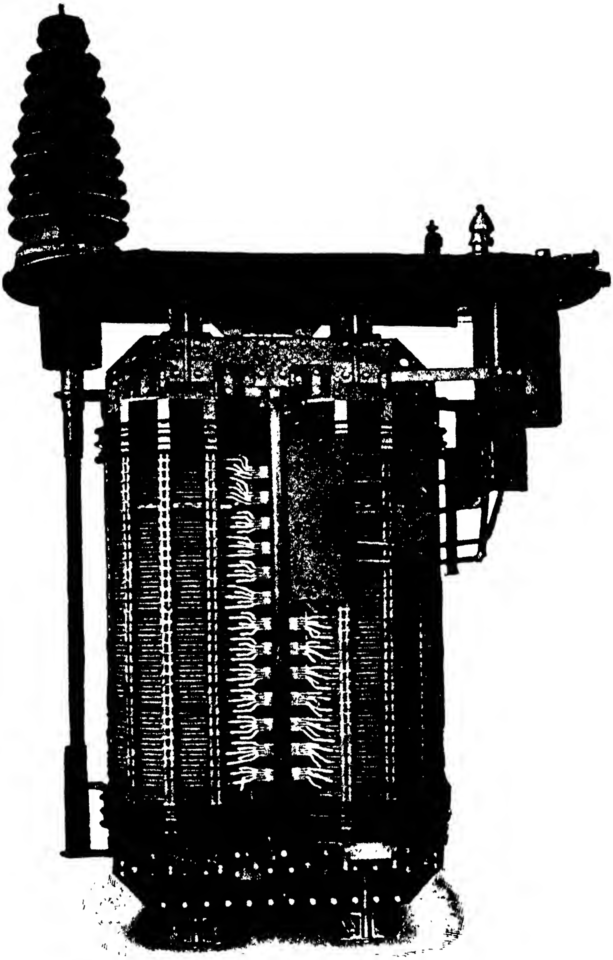


FIG. 60. MEDIUM SIZE PETERSEN COIL, READY ASSEMBLED FOR MOUNTING IN THE TANK

(*A.E.G.*)

considerations. It is known that the magnitude of the resonance voltage possible with an oscillatory, partly iron, inductive circuit, is closely limited by the saturation point of the iron;

the selection of a suitable iron saturation point, therefore, also confers on the arc suppressing coil itself—as recognized by its inventor from the outset—the ability to prevent dangerous resonance voltages.

Impressed electro-motive forces can arise in such an oscillatory circuit for various reasons, and can tend to induce the latter to oscillate due to resonance, so causing an undesirable increment in the voltage of the neutral point to earth. Thus dissymmetry in the number of turns of the three phases of the connecting transformer, which can either exist from the outset or be caused by defects in the windings, can give rise to an impressed e.m.f.

$$E' = \Sigma V_{ph} \quad . \quad . \quad . \quad . \quad . \quad (9)$$

where V_{ph} represents the voltages of the three phases of the transformer. Obviously with a symmetrical transformer, the sum of the three phase voltages is always nil.

Dissymmetries in the capacitance to earth of the different phases of the network have exactly the same effect as if an exciting voltage

$$E' = V_{ph} \times (\Delta C/C) \quad . \quad . \quad . \quad . \quad (10)$$

occurs, where ΔC is the deviation of the capacitance of the unsymmetrical phases from the capacitance of the symmetrical phases, and C the entire capacitance to earth of the network. For instance, with a single-phase network,

$$\Delta C = C_1 - C_2 \text{ and } C = C_1 + C_2,$$

where C_1 and C_2 represent the capacitances of the two conductors to earth.

It is also known, that when another independent transmission system runs parallel to a given line and a superimposition of the mean voltage to earth occurs in the former, the mutual capacitance C_x between both transmission systems has the effect of causing a voltage to be superimposed on the latter line. If V_{ox} is the superimposed voltage to earth of the disturbed transmission system, an exciting voltage

$$E' = V_{ox} \times C_x/(C + C_x) \quad . \quad . \quad . \quad (11)$$

is induced in the oscillatory circuit formed by the earth capacity of the disturbed line and the inductivity of the Petersen arc suppressing coil.

If the Petersen coil were to possess no iron saturation, a resonance voltage

$$V_0 = \frac{E'}{\sqrt{[(R/\omega L)^2 + (1-1/\omega^2 LC)^2]}} \quad . \quad (12)$$

would appear at the terminals of the coil and thus at the neutral point of the network, due to the influence of the exciting voltage E'. With a low circuit resistance R and accurately tuned resonance, it would mean that dangerous over-voltages might arise at the neutral point of the network, and

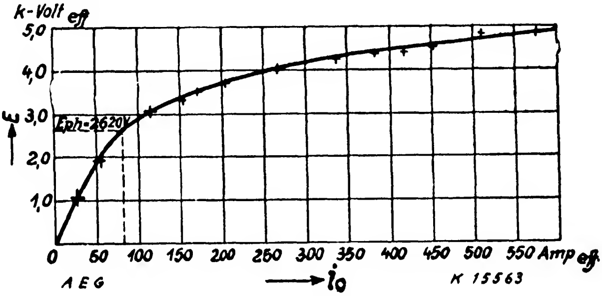


FIG. 61. MAGNETIZATION CURVE OF A PETERSEN COIL (A.E.G.)

thus particularly in the phases having the least capacitance to earth.

Actually, however, and as already indicated, the magnitude of the over-voltage possibly occurring due to resonance is confined to narrow limits on account of the effect of the saturation of the iron core of the Petersen arc suppressing coil.

In Fig. 61 is shown a magnetization curve of a 200-kVA Petersen arc suppressing coil (normal rated voltage 2620 V, line voltage about 4500 V, rated current about 77 A). The curve clearly demonstrates that the saturation phenomena of the iron become very pronounced shortly after the normal voltage is exceeded, and lead to an abrupt bend of the magnetization curve which is characteristic of any closed magnetic circuit.

In order to determine the resonance voltages occurring in an oscillatory circuit possessing self-inductance, the most appropriate way of approach is a graphical method, which will be briefly elucidated by means of Fig. 62.

This method ignores the influence of the ohmic resistance and the distortion of the current and voltage curves, and consequently provides approximate values only. The magnetization curve of the corresponding Petersen coil is plotted on a co-ordinate basis, and the values of the voltage E' which produces the oscillation are plotted as ordinates from zero downwards. It has been presupposed in the example to be 1 kV,

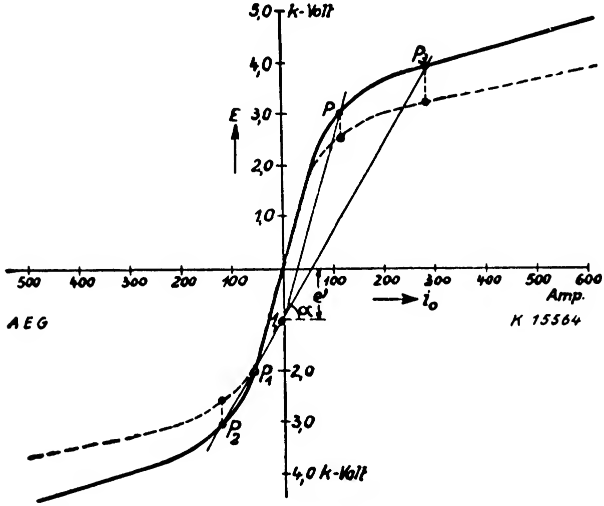


FIG. 62. GRAPHICAL CALCULATION OF RESONANCE VOLTAGE (*A.E.G.*)

or 38 per cent of the phase voltage, a figure which would hardly occur in actual practice; at any rate it would never occur on account of the dissymmetry of the phase capacities to ground under ordinary service conditions. From the point thus resulting, a line is drawn in such a direction that it forms with the horizontal axis an angle α, so that

$$\tan \alpha = 1/\omega C$$

is determined by the capacitive reactance of the network. The magnitude of the resonance voltage occurring at the Petersen arc suppressing coil, and thus at the neutral point of the network, is to be found at the point where this line intersects the magnetization curve. Fig. 62 illustrates two typical cases. In one instance—assuming a non-saturated condition—the capacitive reactance is just equal to the inductive reactance,

and the Petersen coil is approximately tuned to resonance; nevertheless, the point of intersection P gives a resonance voltage which is barely 15 per cent higher than the normal phase voltage (2620 V, see Fig. 61). In the second instance, the capacitive reactance is only half as large as in the first instance, so that the network is greatly under-compensated, and in this case three points of intersection obtain of which, however—as may be proved—point P_2 does not provide a stable condition of oscillation. In the extreme case mentioned, which would hardly ever arise in service, the point of intersection P_3 gives the maximum possible resonance voltage, which is 40 per cent higher than the normal phase voltage. This denotes that, under the most adverse circumstances, the network phases can assume a voltage to earth which exceeds the normal line voltage by an amount that is less than 40 per cent.

The following facts have also to be considered: The graphical method shown in Fig. 62 furnishes the amplitude of the fundamental wave of the resonance voltages occurring at the terminals of the Petersen coil. The voltage of the coil, however, does not follow a sine curve in the presence of considerable over-voltage, in fact, it runs much flatter than the sine curve, as evidenced by Fig. 63, which shows the voltage curves of the Petersen coil resulting for the points of intersection P and P_3 of our example. It must, however, be observed that it is the peak value of the resonance voltage which determines the stress on the insulation, and that therefore this voltage is of particular interest. In the example given, the resonance voltage is about 20 per cent lower than the amplitude of the fundamental wave. The crest value of the over-voltage due to resonance, given by the method of approximation developed in Fig. 62, is therefore too high by this amount. Accordingly, in order to gain a true picture of the actual electrical stress on the insulation of the plant, the correct procedure would be to read off the magnitude of the over-voltage due to resonance not from the magnetization curve (drawn in full), but—as indicated in Fig. 62—from the dotted curve of the voltages in question which are about 20 per cent lower. But this simply suggests that on full compensation, over-voltages due to resonance are practically speaking of no consequence, and that, attributable to the influence of any exciting voltages, no higher voltages than those accompanying every ordinary earth fault can occur at the neutral point of the network,

and hence in the network phases. If the inductance can be thus altered to such an extent by the saturation phenomena in the Petersen coil that considerable over-voltage cannot occur when the voltage augments, there can be no foundation for the charge occasionally raised that the saturation causes the inductance to vary so seriously, even during the usual

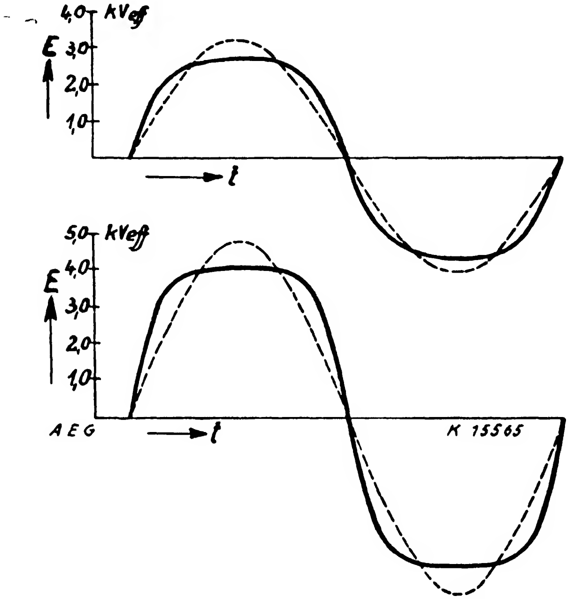


FIG. 63. VOLTAGE CURVES OF A PETERSEN COIL, SHOWING THE EFFECT OF IRON SATURATION

(*A.E.G.*)

fluctuations of the network voltage, that the extinguishing effect is jeopardized.

As may be established readily from an examination of the magnetization curve, the inductance does not vary more than $\pm$ 5 per cent—a figure of no significance in service—at the maximum normal saturation of the iron core of about 15 000 gauss and voltage fluctuations of $\pm$ 10 per cent. Also, the greatest distortion of the current curve in the event of an earth, i.e. at maximum normal saturation, is only about 5 per cent, so that the assertion sometimes made that the residual current is materially augmented by the higher harmonics carries no weight.

In order to adapt the Petersen suppressor to the current to earth of the network, it is furnished with tappings which permit the current through the coil to be adjusted conveniently. Ordinarily, the tapping range is so selected that it is possible to regulate the current within a ratio of 1 : 2. However, the saturation of the iron core of the suppressor also alters, and it will be readily apparent that the corresponding alteration of the saturation in the case just mentioned remains within the limits 1 and 1·4, because, as is known, the inductance of a coil alters with the square of the number of turns, and accordingly the current varies inversely to the square root of the number of turns, and thus with the square of the saturation.

If a much wider regulating range than 1 : 2 is required of the suppressor, recourse is had to designs with several separate magnetic circuits, in order to remain within the above-mentioned range of variation of the saturation of the iron.

The maximum saturation of the iron core of the suppressor, which is chosen about 15 000 gauss at normal phase voltage, is based on Fig. 62, and the numerical results coupled therewith. However, in order to obtain the upper limit for those resonance over-voltages, which can arise when the saturation of the suppressor is at its lowest figure, i.e. at 10 500 gauss—again at normal phase voltage—it is merely necessary to plot anew the full and the broken magnetization curves in Fig. 62 in such a manner that the ordinates are increased by 40 per cent and the abscissae simultaneously shortened in the ratio 1 : 1·4. If we were then to continue our plotting as necessary to ascertain the over-voltage due to resonance, it would be discovered, that when the Petersen arcing ground suppressor is correctly tuned, a voltage not exceeding the normal phase voltage by more than 40 per cent, can occur at the neutral point of the network. Moreover, it must be taken into account that this method ignores the influence of the ohmic resistance, which has the effect of lowering the over-voltage due to resonance; further that a comparatively high exciting voltage E' was assumed, and that finally the point of intersection P lies lower when over-compensation exists, i.e. when the current of the Petersen suppressor is too high. However, as considerable capacitive dissymmetries (which produce resonance over-voltages) are usually due to the capacitance in one or two network phases being reduced by the blowing of single fuses, opening of single pole isolators, or fusing of one or two phase conductors, the

remainder of the system will, in such cases, be left over-compensated by the Petersen coil. From the moment when the exciting voltage E' is set up, i.e. from the commencement of the conditions responsible for the existence of this voltage, until the complete development of the resonance over-voltage, there is a definite time lag, inasmuch as an equalizing oscillation first develops whose current and voltage amplitudes are opposed to those of the stationary condition of resonance. Accordingly, the over-voltage due to resonance first increases gradually up to its value, to that extent in which the equalizing oscillation decreases due to the damping effect. The increment

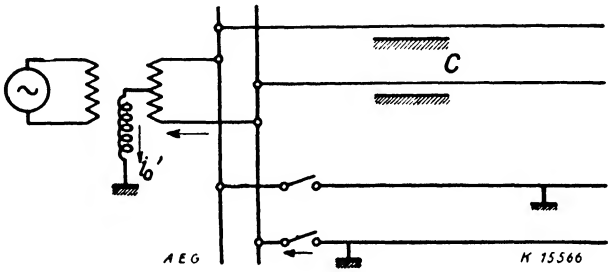


Fig. 64. Two-phase Earth Fault

C Earth capacity of the remainder of lines
i_0' Current through Petersen coil

(*A.E.G.*)

in the over-voltage due to resonance occurs more slowly the lower the watt losses in the oscillatory circuit. In actual service, several cycles are required until the over-voltage due to resonance attains its full value. However, this implies that momentary dissymmetries in the capacitance of the line—as may result through the phases of three-phase isolating switches or circuit-breakers not being closed simultaneously—do not cause any appreciable voltage to be superimposed at the neutral point of the network, on account of their brief duration.

There is only one instance in which the Petersen coil can be the cause of considerable over-voltage. In the network represented in Fig. 64, a two-phase earth leads to superimposition of the voltage at the neutral point, whereby it may be assumed that in the most favourable case, 70 per cent of the phase voltage occurs between the neutral point of the network and earth. The short-circuit current across both earthed points has a phase displacement from the exciting voltage of about

40° to 60°, whereas the current consumed by the Petersen coil lags the impressed voltage by approximately 90°. Accordingly, there is a phase displacement of about 45° between the short-circuit current and the current traversing the suppressor, so that when the latter is ruptured at the instant at which the short-circuit current passes through zero, it still possesses an instantaneous value—measured as r.m.s. value—which approximates to

$$I'_0 = 0{\cdot}7 \sin 45° \, I_0 \simeq 0{\cdot}5 \times I_0,$$

where I_0 is the current consumed by the Peterson coil at at phase voltage. The current in the coil having the instantaneous value so calculated, would have to flow through the short-circuit arc—which is much too long for it—after the short-circuit current is extinguished. As, however, this low current intensity is by no means sufficient to maintain the arc, the latter extinguishes suddenly, and therefore a rupturing voltage occurs at the Petersen coil. This voltage can be calculated if it be considered that the suddenly released magnetic energy of the Petersen coil is stored in the form of electrostatic energy in the capacity to earth (C in Fig. 64) of the transmission system remaining connected to the transformer after disconnecting the double-pole earth. The equation thus obtained is

$$\tfrac{1}{2} I'^2_0 L = \tfrac{1}{2} V_c^2 C \quad . \quad . \quad . \quad . \quad (13)$$

whereby the over-voltage accompanying disconnection amounts to

$$V_c = I'_0 \sqrt{(L/C)} \quad . \quad . \quad . \quad . \quad (13a)$$

An example selected as representing a typical case will furnish a conception of the magnitude of the excess voltages to be anticipated.

It is presupposed that a Petersen coil for a normal current rating of 100 A is installed in a 100-kV network, so that the equipment possesses an inductance of $L \simeq 2$ henries. A two-phase earth, which gives rise to superimposed voltage at the neutral point amounting to 70 per cent of the normal phase voltage, is cut off, whereupon 15 miles of the line remain connected to the supply transformer. A three-phase line of this length possesses a capacity to earth of $C \sim \frac{1}{4} \mu F$, and with the aid of this assumption it is possible to compute the

over-voltage to be anticipated when rupturing the double-pole earth as

$$V_c = 50\sqrt{[(2/\tfrac{1}{4}) \times 10^6]} = 140\,000 \text{ V}.$$

It will be recognized that the over-voltage remains within reasonable limits, despite the comparatively short section of the line still in service. Under practical conditions, and particularly in systems of lower voltages, the over-voltage caused by the coil in the event of a double earth fault is negligible. At the same time, the fact should not be ignored that two-phase earths are rare occurrences. The over-voltage in question is, moreover, rendered impossible if the Petersen coils are installed in the substations of the network instead of in the main station; because then the network voltage falls to such an extent on the occurrence of a two-phase earth that the coil no longer carries any appreciable current.

APPLICATION OF PETERSEN COILS TO UNDERGROUND CABLE SYSTEMS. The Petersen coil is also usefully applied in connection with underground cable feeders, where almost every fault starts between a conductor and earth. Here, still more than on overhead lines, is a tendency of earth faults to develop into a short-circuit between phases, resulting in the burn-out of a considerable length of cable. Also earth currents, due to the high cable capacitance, are extremely heavy in underground feeders. Values of several hundreds or even thousands of amperes are quite common in large networks.

By the action of the coil the current through an earth fault is reduced to a fraction of these values, but, in contrast to transient faults in overhead networks the residual fault current will not disappear; still the fault need not be isolated at once, but may be allowed to remain in circuit for a little while, the duration of which is dependent on the value of the residual current and on the type of cable. Modern cables with separate metal sheaths over each conductor permit the residual earth current to persist for one hour and more before developing into a multi-phase short-circuit. This gain of time is most valuable, as it allows the switching operations for the isolation of the faulty section to be carried out without undue hurry.

Though, in view of the heavy earth currents, the cost of Petersen coils for underground cable feeders or networks is considerable, their installation is rapidly becoming general practice, particularly in connection with cables for the highest voltages.

Tuning of Petersen Coils. In *overhead systems*, as has been mentioned before, the tuning of the coil need not be very accurate. It is, therefore, usually sufficient to select the proper tapping by means of a scale giving the earth current for each line section actually in operation.

For *underground cables* this method would be inadequate. In view of the high value of capacity current, it is essential to keep the fault current down to a minimum. For this purpose a special instrument, the *compensometer*,* has been developed

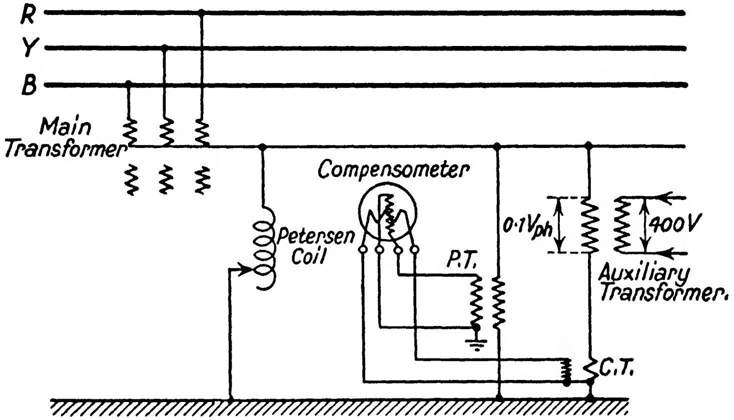


Fig. 65. Compensometer Connection for Underground Cable Networks

which indicates the amount of under- or over-compensation at any time. This instrument measures the line reactance directly, thus taking into account the variation of capacity due to switching operations or other causes. The use of a compensometer is particularly advantageous where a number of Petersen coils are connected to one network, since thereby each coil can always be tuned in such a way as to give full compensation in co-operation with the others.

Fig. 65 shows the connection of a compensometer to an underground cable system. The instrument itself is energized by the neutral voltage and the current in the neutral circuit. In order to make the measurement independent of incidental influences, a constant voltage of, say, 10 per cent of the phase voltage is imposed by means of an auxiliary transformer.

* See Bibliography No. 23.

According to equation (6) the combined capacitance of a symmetrical three-phase system may be replaced by an imaginary capacitance of $3C_{ph}$. With one or several Petersen coils (having a combined inductance L_p) in circuit, the resulting reactance of the earth circuit

$$X_E = \frac{1}{2\pi f \times 3C_{ph} - 1/[2\pi f \times L_p]} \quad . \quad . \quad (14)$$

is a direct measurement for the wattless component of the residual earth current

$$I_{EX} = V_{ph}/X_E \quad . \quad . \quad . \quad . \quad . \quad (15)$$

This wattless current is zero when equation (8) is satisfied, i.e. when the system is correctly compensated. The scale of the instrument is calibrated for the current I_{EX} and indicates whether the current is leading or lagging.

In very extensive *overhead systems* the use of a compensometer is also desirable. In this case, the potential between the neutral and earth would be substantially influenced by the capacitance of the three phases being unbalanced. Instead of an auxiliary transformer an auxiliary alternator is therefore used, with a frequency different from that of the main circuit. The auxiliary alternator requires protection from being damaged by the high neutral voltage appearing on its terminals in the event of an earth fault. For this purpose a protective coil (which may be one of the Petersen coils) is inserted. As soon as a fault occurs, the auxiliary alternator is short-circuited and stopped.

Fig. 66 shows the complete connections of a compensometer equipment for a 100-kV overhead system. In this case the voltage in the auxiliary circuit is 6 kV, and the auxiliary alternator *G* is not connected directly, but through an auxiliary transformer *Tr* which is protected by the Petersen coil *PC*. The required output of the auxiliary alternator is approximately 1 per cent of the earth fault energy, i.e. under normal conditions between 1 and 100 kVA.

Earth Leakage Protection. Unless a Petersen coil is used, high steep-fronted surges may be caused on a system with insulated neutral by an intermittent arc to earth. If the neutral is solidly earthed, no such excess voltages can be set up, but in that case every single earth fault short-circuits one phase of the system, and this short-circuit threatens to spread quickly to other phases. In both cases the faulty line section must be

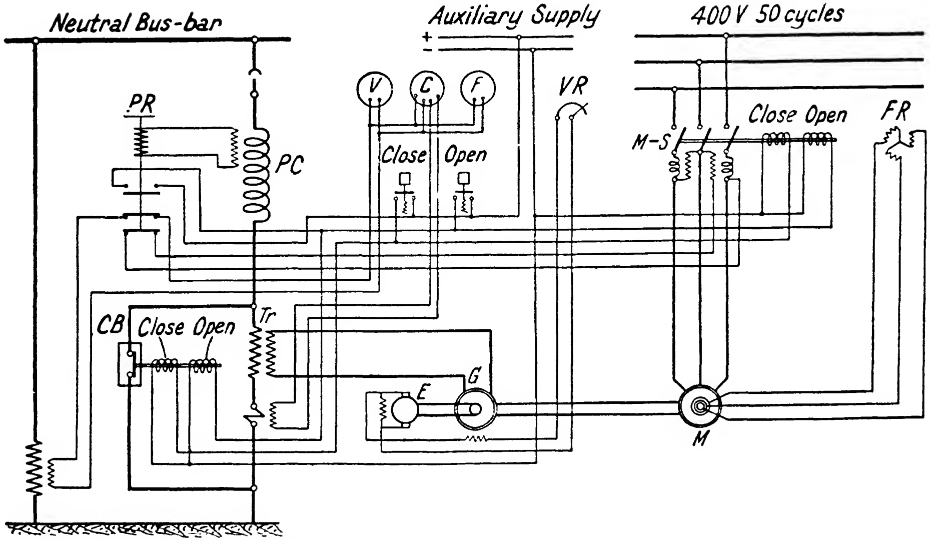


Fig. 66. Compensometer Connection for Overhead Lines

C	Compensometer	*M*	Motor	*PR*	Protective relay
V	Voltmeter	*M-S*	Motor switch	*VR*	Voltage regulator
F	Frequency meter	*Tr*	Transformer	*FR*	Frequency regulator
G	Generator	*CB*	Circuit-breaker	*PC*	Petersen coil
E	Exciter				

cleared as rapidly as possible. This task is performed by an earth leakage relay. Even in a system protected by a Petersen coil, the use of earth relays is advisable, in order to indicate in which section an earth fault has occurred, or prevails.

Earth relays may be operated—

(*a*) By the voltage between the faulty conductor and earth, which is greatly reduced in the event of an earth fault;

(*b*) By the voltage between a healthy conductor and earth, which is increased up to $\sqrt{3}$ times its normal value;

(*c*) By the voltage between the neutral and earth, which is nil under normal, but up to phase voltage under fault conditions;

(*d*) By the earth current, or out-of-balance current in the mutual secondary circuit of three current transformers.

Methods (*b*) and (*c*) are only applicable on systems with insulated neutral. Where a Petersen coil is installed, the current through it, which is equal, though in phase opposition to the leading current, may be taken as a direct indication of an earth fault. Petersen coils are also provided with a secondary voltage winding (see Fig. 57), which may be used for indicating or recording purposes.

Split Conductor System. For use on systems with solidly earthed neutral, the split conductor system is another efficient means of earth leakage protection. This well-known system requires each feeder, including the contacts of connecting circuit-breakers, to consist of two halves slightly insulated from each other. Later modifications permit the use of standard single contact circuit-breakers. One of them, the Pfannkuch system, which is also applicable to ring main feeder sections, will be dealt with in Chapter VII.

Lightning. Overhead transmission lines are exposed to direct interference through atmospherically induced voltages, either by induction or by being directly struck by lightning. Both causes lead to a temporary increase of line potential often far in excess of the impulse flash-over voltage of line insulators. The number of occasions on which conductors are directly struck can be greatly reduced by the installation of earth wires and the suitable arrangement of the conductors. Statistical records suggest that an arrangement with all conductors in one plane (Fig. 67), and with one earth wire above each circuit,

presents the highest safety from lightning trouble. Such an arrangement, combined with the use of hinged brackets, incidentally also gives the greatest safety against the risk of two wires touching each other, and imposes the least stress on the suspension towers in the event of one or several conductors breaking.

So-called backward flash-overs from a struck tower to one

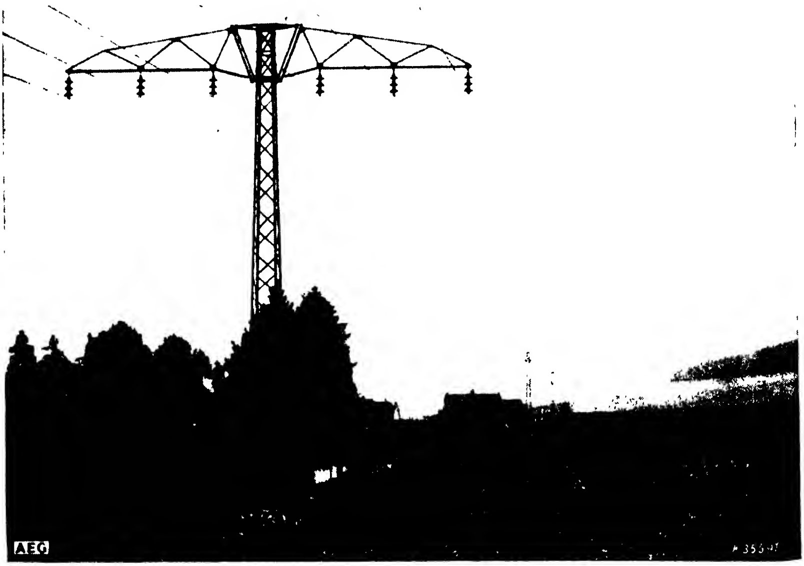


FIG. 67. ARRANGEMENT OF CONDUCTORS IN ONE PLANE (*A.E.G.*)

or several conductors are safely averted by means of effective earthing of all steel towers.* The footing resistance may be reduced by copper cables buried in the soil, either along the line or in a radial direction. If, by such means, the footing resistance of each tower is reduced to a sufficiently low value† and an earth wire is installed above each circuit, a line may be considered reasonably proof against lightning trouble.

Direct strokes of lightning on to steel towers are thus made harmless. Occasional damage to wooden poles, however, can hardly be averted.

* See Bibliography Nos. 48 and 53.
† See Bibliography No. 53, p. 250.

Direct strokes on to a conductor with voltages of many millions are immediately transformed into surges travelling in both directions with nearly the velocity of light. Almost immediately the crest of the surge is reduced to the corona voltage. Within about the same time a flash-over to earth occurs on a weak spot, i.e. as a rule across an insulator, where earthed parts are nearest to the conductor. Arcing horns or rings are not a sufficient safeguard against the enormous energy

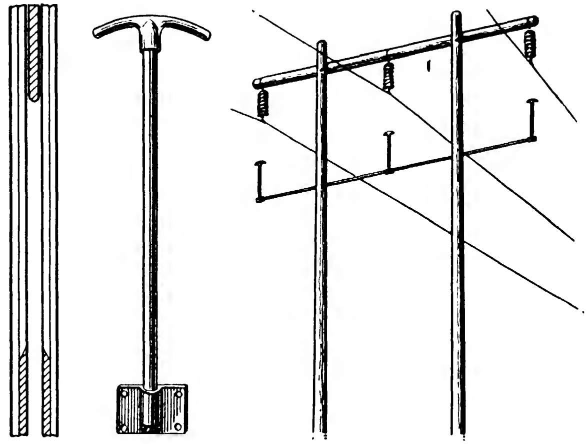


FIG. 68. EXPULSION GAP

discharged in such an event. It must be noted that it is very often not the discharge of the excess voltage itself which destroys the insulator, but the operating current following through the ionized arc path. In the U.S.A. so-called *expulsion protective gaps* have been tried out with some success. Their object is merely to prevent destruction of an insulator by a flash-over arc. Fig. 68 shows the design of an expulsion gap, and the way it is mounted on a pole. While such gaps are only applicable on systems with earthed neutral, the same object is achieved in a system with insulated neutral by a Petersen coil.

The expulsion protective gap consists of a fibre tube with one end closed and the other open. The internal flash-over voltage is made lower than the external by having an electrode at one end projecting into the tube, and a tubular electrode

at the discharge end. The flash-over voltage of the complete unit is less than that of the string of insulators which it is to protect.

Each size of expulsion gap has a limited range of rupturing capacity. If the power current following the discharge is smaller than the minimum rating, the expulsion action is not sufficient to extinguish the arc. On the other hand, an excessive current is liable to burst the tube through the high pressure generated. If the correct size is employed, the arc is usually extinguished within one or two half cycles. Frequent operation causes erosion of the inside of the tube and thus raises the minimum rating.

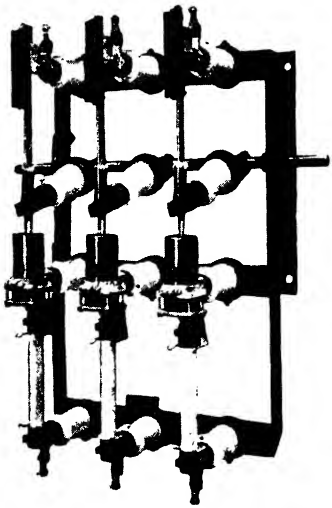


FIG. 69. MODERN SWITCH FUSE
The switch is capable of interrupting normal full-load current.
(*A.E.G.*)

On its further travel along the line, the energy of a surge is gradually attenuated by the resistance and leakage of the line. The surge does not constitute a further menace until it reaches a station; means to protect transformers and switchgear have been indicated in the preceding chapter.

Excess Current. The oldest means of protection is the fuse. Its well-known disadvantages are the necessity for replacement following every operation; the inaccuracy of the fusing current under persistent overload; and the interruption of only one phase in case of earth faults. Nevertheless, the fuse has retained, and always will have, a wide field of application. With the progress of rural electrification, this field is even growing. Fuse designs have been greatly improved, and their performance under heavy short-circuits is sometimes even superior to that of circuit-breakers (see pp. 56–58).

Fig. 69 illustrates a modern 11-kV switch-fuse. The pressure in the small open explosion pots is caused by evaporation of a liquid or, preferably, of material from the wall of the pot.*

In the event of a short-circuit in apparatus connected to a

* E.T.Z., 1935, p. 1189.

feeder comprising several sections, it is, of course, not desirable that the entire feeder should be disconnected on this account. It is, therefore, necessary to provide such time grading of fuses or excess current relays, that the least possible length of line is affected by the unavoidable interruption. In the case of relays, this is achieved by a graded time protection, with time lags increasing towards the supply end. The two fundamental systems using a definite time lag or a time lag inversely varying with the fault current, with a definite minimum time,

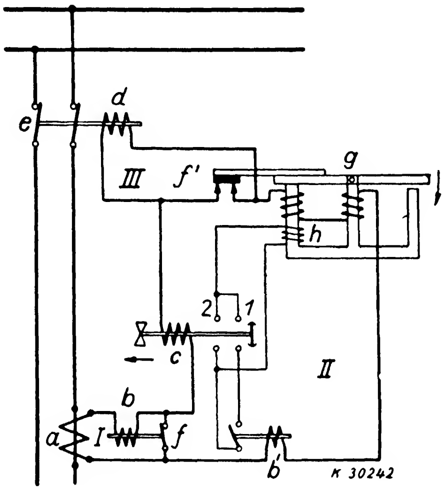


FIG. 70. PRINCIPLE OF STEPPED TIME EXCESS CURRENT RELAY (A.E.G.)

a Current transformer
b, *b'* Excess current coils
c Two-step time element
d Tripping coil
e Circuit-breaker
f Starting contact
f' Tripping contact
g Magnetic system
h Balancing coil

and their respective merits are general knowledge. Their common disadvantage is the fact that the heaviest faults, i.e. those nearest to the supply end, are dealt with by relays having the highest time setting. Where the output of generators feeding into the line varies within wide limits, the definite minimum time lag may also be excessive at times of light load, in particular when a fault occurs near the supply end. This time lag may lead to alternators or motors being thrown out of synchronism.

In order to achieve short releasing times under all circumstances, excess current relays with two or three definite time steps have recently been gaining favour abroad.* Their principle is illustrated by Fig. 70. If the adjusted current limit is exceeded, a multi-step time switch *c* is set in motion, by means of the coil *b* opening its contact *f*.

* See Bibliography No. 28.

If the fault current is very heavy, contact b' closes and as soon as the contact 1 of the time element short-circuits the winding h, the magnetic balance of the system g is disturbed, contact f' is opened and the circuit-breaker trips. With smaller fault currents contact b' does not close, and the relay cannot operate until contact 2 of the time element does close.

Fig. 71 illustrates an example of feeder protection by relays with two definite time steps in stations a and b, and with

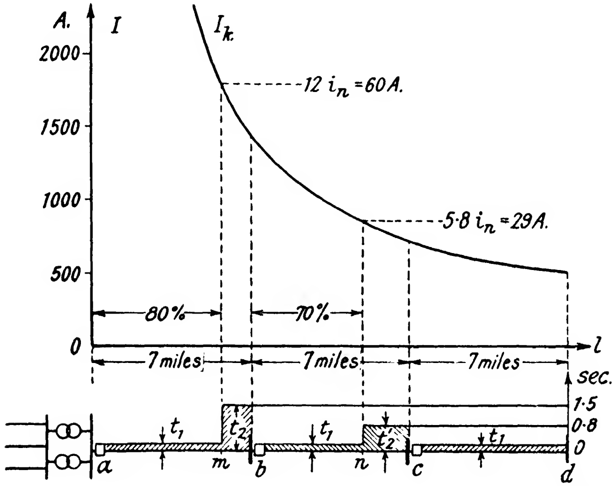


FIG. 71. TRIPPING CHARACTERISTICS OF STEPPED TIME EXCESS CURRENT PROTECTION

a, b, c, d Stations
i_r Rated secondary current of current transformers I_k Short-circuit current.
t_1 Time lag on first step of relays t_2, t'_2 Time lag on second step of relays

single-step relays at c. In the case of three-phase short-circuits occurring anywhere on the line, which are not accompanied by a noticeable voltage drop at a, the respective short-circuit currents would be indicated by the curve. For instance, a three-phase short-circuit on the right of, and not far from station b will cause a fault current of 1400 A. With a current transformer ratio of 150/5 this is equivalent to a relay current of about 47 A. In the instance of the coils b' (Fig. 70) in stations a and b being set to close their contacts when the current exceeds 60 A and 29 A respectively, relays at b will operate in the minimum time, whereas at a the contacts b' will not be closed, and these relays will not operate unless relays at b fail.

A certain overlap is required in view of the fact that short-circuit currents may vary to a certain extent. In the event of two-phase short-circuits, currents are about 13·3 per cent lower,* and the amount of overlap is then accordingly higher.

If the supply voltage at *a* drops, fault currents are further reduced and the overlap increases, i.e. point *m* moves towards *a*, and *n* towards *b*. In view of the lower currents, such faults are not dangerous, so that the increased time lag (up to 1·5 seconds in Fig. 71) is then permissible. Fig. 72 is an illustration of a relay with three adjustable time steps, designed on this new and promising principle.

FIG. 72. THREE-STEP TIME RELAY (*A.E.G.*)

TEES. The practice of teeing the supply to groups of small consumers off main feeders is increasing with the growth of rural electrification. It is necessary to apply protective systems which are not too costly, and which do not cause the disconnection of the main feeder in the event of a fault on the tee. Here is a field of application for high power fuses as they are now available up to the highest voltages. (See p. 56.)

PARALLEL FEEDERS. Special attention must be paid to the method used for the protection of several feeders joined together at both ends. In this case the automatic gear, besides complying with all requirements of single feeder protection, must isolate only the one feeder on which the fault has actually occurred, without impairing the operation of others.

As long as conditions are normal, a certain ratio prevails between the currents in individual feeders. Through the occurrence of a fault in one of them, the ratio is altered. A differential system is clearly indicated for protection. Several varieties are applicable.

An example is shown in Fig. 73. All the current transformers have the same secondary current i, which circulates in the current transformer circuit. A fault in one feeder causes a larger flow of current $i + \Delta i$ in the appropriate current trans-

* See Chapter I, p. 2.

former; hence, as may be seen from Fig. 73, a current Δi passes through two of the relays. The isolation of the faulty feeder is obtained by suitable connection of their contacts. Differential current relays are used; these are as a rule fitted

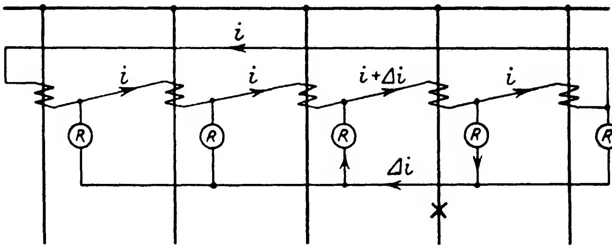


FIG. 73. CIRCULATING CURRENT PROTECTION FOR PARALLEL FEEDERS
R - Relay X - Fault

with biasing devices (see Chapter III) and may be of various designs.

Another variety of differential protection for parallel feeders is represented in Fig. 74. In this case, relays of the balanced or biased type must be employed; Fig. 74 shows the connections for beam relays. Under normal conditions, the secondary

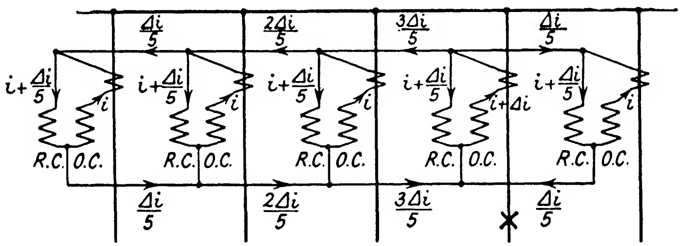


FIG. 74. PARALLEL FEEDER PROTECTION WITH BEAM RELAYS
O.C. = Operating coil R.C. = Restraint coil X = Fault

current i of each current transformer circulates through both coils of the appropriate relay. When a fault occurs in one of the feeders, the additional current Δi flows through the operating coil of the appropriate relay, causing its operation, and returns through all the restraint coils.

If two or three parallel feeders are fed from one end only, the above system is not satisfactory, in particular when the fault occurs near the remote end, and the fault currents in the two feeders are almost equal. The use of directional (reverse power)

relays is then necessary at the remote end. In order to render these reverse power relays operative, even when the reverse fault current is offset by forward load current, and to prevent faulty operation due to simultaneous momentary reverse current surges in all the parallel feeders, circulating current connections are applied (Fig. 75). Another directional and highly sensitive protective system makes use of a wattmeter relay, with its two coils so connected that one of them receives the sum, the other the difference of the two currents. The relay therefore is energized by

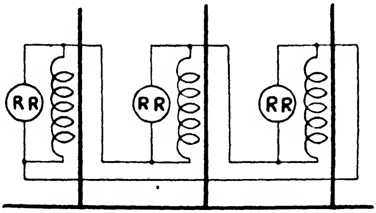


FIG. 75. DIFFERENTIAL REVERSE POWER PROTECTION FOR THE REMOTE END OF PARALLEL FEEDERS
("*Automatic Protective Gear*"—*Henderson*)

$$(i_1 + i_2) \times (i_1 - i_2) = i_1^2 - i_2^2 \quad . \quad . \quad (16)$$

i.e. by the difference of the squares of the currents. This system is universally applicable to both ends, with feeders fed from one or two ends.

Where two lines or circuits with insulated neutral are running parallel over an appreciable length, an earth fault on the one leads to an induced unbalance in the other. In such cases it is necessary to eliminate the undesired interference by installing, in addition to the Petersen coil, suitable balancing coils also.*

Temperature Control. The setting of protective relays is normally determined by the "rated" current of conductors. The rating is based on the rise of temperature above a specified maximum temperature of the ambient air or soil. This method of rating is generally applicable, and is easily complied with, but it results in very incomplete utilization of the active material. If, for instance, the ambient temperature happens to be very low, the actual temperature of a conductor will be much below the permissible maximum, even when loaded with the highest permissible current.

In fact, the permissible load limit is not related to temperature rise at all, but is determined by the temperature which the conductor actually reaches, provided, of course, that no lower limit is imposed by other considerations. The permissible loading from a thermal point of view varies according to the

* See Bibliography No. 22.

temperature, humidity and other circumstances. Direct measurement of conductor temperature is, therefore, a most valuable means of increasing the efficiency and reliability of

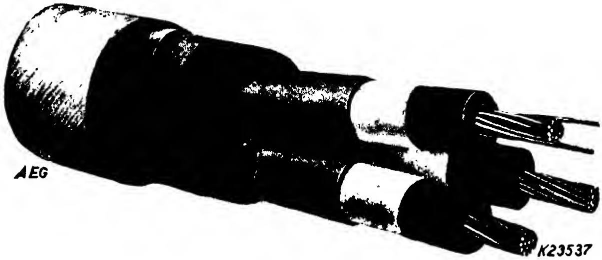


Fig. 76. Cable with Auxiliary Wires for Temperature Control
(*A.E.G.*)

operation. By adjusting relay settings to the external conditions prevailing at any time, the premature disconnection of important feeders, such as coupling lines between two main power stations, can often be averted.

In the case of underground cables, the means for accomplishing this important improvement are two auxiliary wires in a short length of cable (Fig. 76), connected by a small transformer to a suitable recording or indicating instrument.

CHAPTER VII

H.T. RING MAINS

THE selective protection of feeder sections forming part of a ring main system is one of the most important, and at the same time difficult, problems. The ideal solution would be a system without pilot wires or other means of communication between the two ends of the protected section, operating instantaneously in case of a fault anywhere within, and with a graded time lag in case of faults outside the section. The principal schemes that have been developed for this purpose are described below; it will be seen that a completely satisfactory solution is still lacking, though several modern systems very closely approach the ideal.

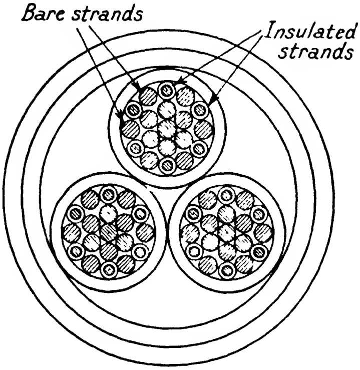


FIG. 77. CROSS-SECTION THROUGH PFANNKUCH CABLE

Split Conductor Systems for Underground Cable Networks. In its original form,* the split conductor system is not applicable to ring main systems; it has the further disadvantage of requiring expensive six-phase cables and circuit-breakers with split contacts. Also, the original system does not respond in the event of a breakdown of the insulation between two splits.

All these disadvantages are eliminated in the Pfannkuch system of cable protection. The Pfannkuch cable (Fig. 77) differs from a standard three-core cable only in that half the strands of the outermost layer of each conductor are slightly insulated from the remainder. The outer layer of each conductor thus consists of bare strands, alternating with insulated ones. These insulated strands share in the transmission of the main current, but a small auxiliary voltage is also maintained between them. For this purpose they are connected in such a way as to form two groups. Originally, the auxiliary

* See p. 88.

voltage was derived from special current transformers, but in order to make the system operative on unloaded cables, preference was given in later schemes to a constant voltage from auxiliary or potential transformers. Where the reactance of the protected cable section is comparatively low, the auxiliary voltage may be taken from both ends of a line section (Fig. 78); where the reactance is high, the two auxiliary voltages will differ from each other to such an extent as to cause faulty operation in the event of a fault external to the protected section. Therefore, an improved scheme has been developed with auxiliary voltage supply from one end only.

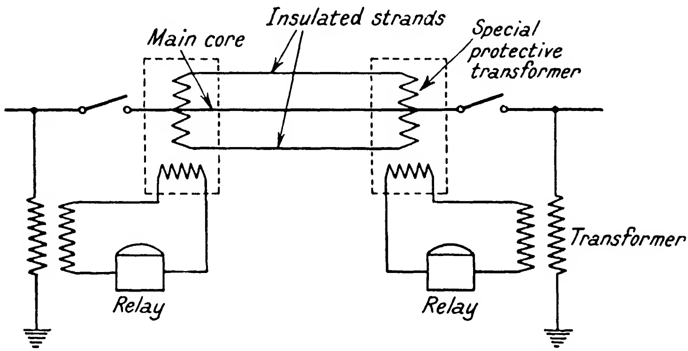


FIG. 78. PRINCIPLE OF PFANNKUCH PROTECTION
(Auxiliary voltage supplied to both ends)

In both cases any slight fault current to earth, or between phases, will carbonize the insulation of the insulated strands, and thus create a path of low resistance for auxiliary current to circulate between neighbouring insulated strands. This current is carried through suitable alarm and tripping relays. The system avoids special contacts on circuit-breakers, but requires triple isolators in each phase. Since every fault is detected and indicated in its initial stage, and a heavy fault leads to instantaneous and selective disconnection; since further no pilot wires are required and the extra cost of a Pfannkuch cable over standard cable is negligible, this system of protection is the most perfect available for underground cables.

The small disadvantage of having to use special isolators will not carry much weight. More important is the fact that the system leaves the bus-bars between cable sections unprotected.

It is, however, comparatively easy to provide an additional secondary winding for the connection of circulating current relays on each of the Pfannkuch auxiliary transformers; incidentally these transformers may be of the bushing type.

The complete connections of a system with auxiliary voltage feeding from both ends are shown in Fig. 79. The relays used

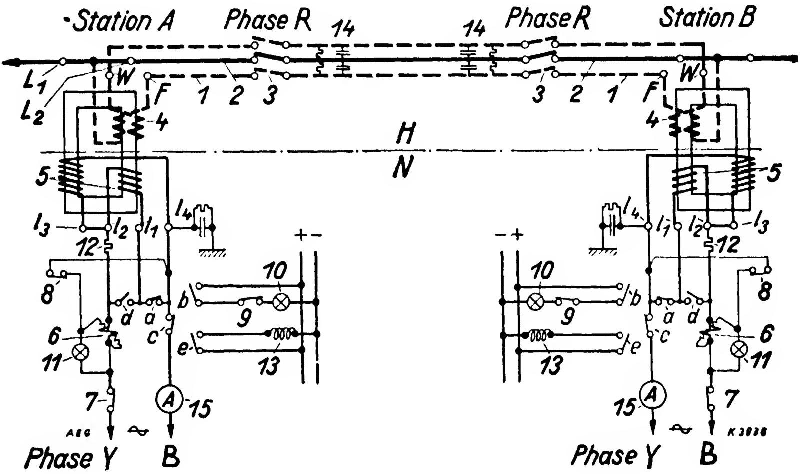


FIG. 79. COMPLETE DIAGRAM OF PFANNKUCH PROTECTION

With auxiliary voltage supplied from both ends

A, *B* = Stations
H = High tension
N = Low tension
1 = Insulated strands
2 = Main core
3 = Isolator
4 = H.T. secondary of protective transformer
5 = Primary winding of protective transformer
6 = Wattmeter system
7 = Current switch
8 = Potential switch
9 = Indicating lamp switch
10 = Alarm lamp
11 = Indicating lamp
12 = Series resistance
13 = Circuit-breaker trip coil
14 = Bridging condensers
15 = Ammeter
a, *b*, *c*, *d*, *e* = Relay contacts
L_1, L_2, *F*, *W* = H.T. terminals of protective transformer
l_1, l_2, l_3, l_4 = L.T. terminals of protective transformer

(*A.E.G.*)

are of the wattmeter type and have five contacts (*a* to *e* in Fig. 79), controlling respectively an alarm circuit, the change-over of auxiliary transformer and relay connections, and the tripping circuit. A sixth contact supervises the losses of the auxiliary transformer and operates the relay in case of an internal fault.

The two groups of insulated strands are connected to two equal coils (4) on the auxiliary transformer, opposing each other,

so that under normal conditions the magnitude of the current has no influence on the flux in the core. When a fault upsets the balance between the two coils, or in case of an internal fault in the auxiliary transformer, the relay operates, thereby closing contact *b* and opening *a*. Thus alarm is given, and at the same time the auxiliary voltage is reduced to about

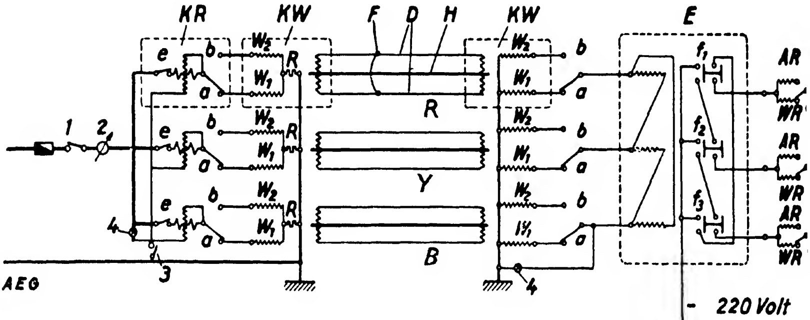


FIG. 80. PFANNKUCH PROTECTION

With auxiliary voltage supplied from one end, with earth leakage indication at the remote end

- D = Insulated strands
- H = Main core
- F = Fault
- KW = Protective transformer
- W_1 W_2 = L.T. Windings of protective transformer
- KR = Protective relay
- a, b, e = Contacts in a.c. circuit
- c, d = Contacts in d.c. circuit
- AR = Tripping coil of protective relay
- WR = Alarm coil of protective relay
- E = Earth leakage indicating relay
- f_1, f_2, f_3 = Twin contacts of earth leakage indicating relay
- R = Series resistances
- 1 = Current switch
- 2 = Ammeter
- 3 = Potential switch
- 4 = Signalling lamp

(*A.E.G.*)

60 per cent of its full value; this reduction is due to the disconnection of winding l_1, l_2. Incidentally, it may be mentioned that the voltage supplied to each relay is that between the two other phases, so that operation is ensured even with a dead short in the immediate neighbourhood. The sudden reduction of voltage also reduces the load on the wattmeter relay. Thus, the relay returns into its normal position and is ready for a second operation, which actually occurs when the fault develops further. This time, contacts *c*, *d* and *e* are operated, and the circuit-breaker trips.

The improved scheme referred to before, for use on cable sections of high reactance, where a considerable voltage drop might appear between the two ends, is represented in Fig. 80. Here the auxiliary voltage is injected only from one (in Fig. 80, the left) end. At this end the connections are

similar to those of Fig. 79. The main difference is that the auxiliary voltage is not a three-phase system, but the same single-phase voltage is supplied to the insulated strands of all three phases. On the remote end, the wattmeter relays are not duplicated; a three-phase earth relay E is provided instead. When one of the wattmeter relays (say that in phase I) operates for the first time, its selector contact is switched over from a to b; thus, the voltage between the two groups of insulated strands D is reduced in that phase, and the phases I and III of the earth relay operate, closing their contacts f_1 and f_3. Thereby the alarm circuit WR_1 is energized, and the selector contacts in phase I are transferred from a to b and from d to c. Thus, balance is restored in the earth relay circuit, so that contacts f_1 and f_3 return to the open position. A second operation follows if the fault develops further, this time causing the breakers at both ends to trip.

The sensitivity of the system can be further improved by means of a small inductance connected in parallel with the voltage path of the wattmeter relay. This coil compensates the influence of the no-load losses of protective transformers.

All varieties of Pfannkuch protection are applicable to systems with earthed or insulated neutral. In systems protected by a Petersen coil the fault current to earth is suppressed by the action of the coil. In this case, however, the initial short kick of earth current may be and usually is sufficient to create a slightly carbonized path between the insulated and the bare outer strands, so that the relays indicate the location of the fault, without causing an unnecessary interruption.

Pilot Wire Systems of Protection. As long as ring mains or interconnected h.t. networks cover a comparatively small area, pilot wire systems may be used for their protection.

OPPOSED-VOLTAGE DIFFERENTIAL SYSTEMS. The original Merz-Price scheme (Fig. 81) suffers from one great drawback, apart from the necessity of using pilot wires, namely, that expensive balanced current transformers must be employed. Even so, the resulting sensitivity remains rather poor. Furthermore, there is a tendency for the relays to operate on capacity current flowing in the pilot wires.

The outcome of endeavours to liberate the opposed voltage system from its inherent disadvantages is that a number of improved varieties are now available*. The application of

* For full particulars see Bibliography Nos. 3 to 5.

sheathed pilots is one means of overcoming, to a certain degree, the difficulties due to capacity currents. Highly sensitive relays have been designed, and their action on through fault

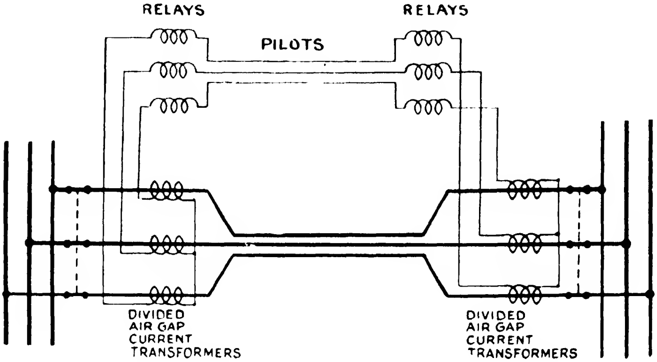


FIG. 81. MERZ-PRICE OPPOSED VOLTAGE SYSTEM
("*Automatic Protective Gear*" (*Henderson*))

currents is prevented by instantaneous-acting diverter relays. The introduction of static bias by means of biasing transformers makes it possible to obtain satisfactory operation with normal relays and with ordinary pilot wires. Another more

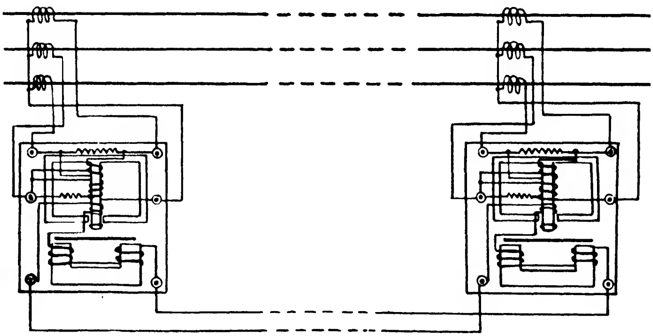


FIG. 82. "TRANSLAY" PROTECTIVE SYSTEM
(*Metropolitan-Vickers Electrical Co.*)

recent modification of the opposed-voltage principle is the "Translay" protective system (Fig. 82). In this case, an induction type relay is employed. The relay has two magnetic circuits, the upper having three windings, two primaries and

one secondary. One of the primary windings is connected across two current transformers and acts in case of a multiphase short-circuit. The second primary is connected between the centre-point of the first primary and the star point of the three current transformers. The secondary winding on the upper, and the winding on the lower magnetic circuit are connected to the pilots, and act as opposed-voltage transformers. In a relay of this type, capacity current in the pilot

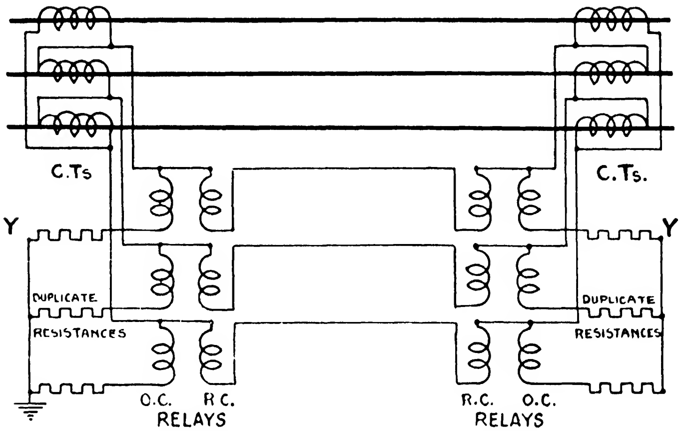


FIG. 83. MCCOLL BIASED CIRCULATING CURRENT PROTECTIVE SYSTEM

("*Automatic Protective Gear*" (*Henderson*))

wire causes backward rotation of the disc, and cannot lead to faulty operation. The system is suitable for use with bushing type current transformers.

Circulating Current Differential Systems. Another successful differential system for the protection of ring mains operates on the circulating current principle. Its advantage over opposed-voltage systems lies in the fact that it is not rendered inoperative in the event of breakage of a pilot wire. Though operation may, in such a case, be caused by a through fault, this is usually considered preferable to non-operation and the false sense of security which would arise, were opposed-voltage gear used. An example of a McColl biased circulating current system is illustrated in Fig. 83. The relays here employed are of the biased beam type; they are connected to ordinary bushing type current transformers and resistances.

As distinct from the original circulating current system, there are no equipotential points. Circulating current passes through the restraining coils; the operating coils and resistances are star-connected. If the ohmic value of each resistance is made equal to that of a relay coil and half of one pilot wire, the same amount of circulating current would also flow through the operating coils. The actions of the two coils on each relay balance each other, and the beam is kept in its normal

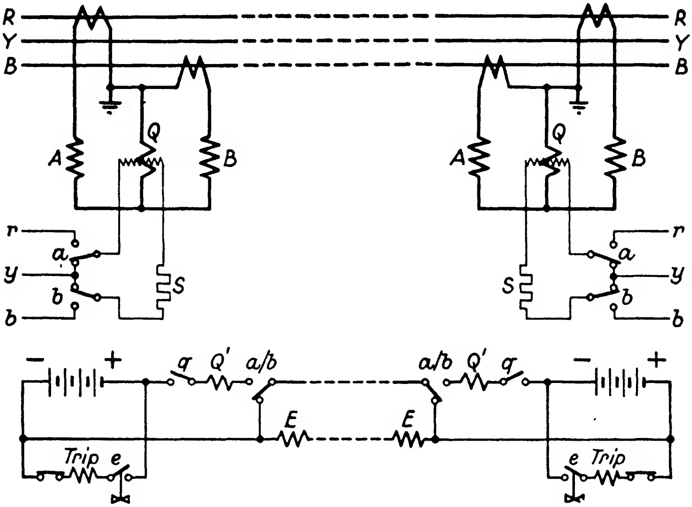


FIG. 84. DIRECTIONAL BALANCE SYSTEM FOR LINES ENERGISED FROM ONE OR BOTH ENDS

A/a, B/b = Excess-current starting elements E/e = Tripping element
Q/q = Directional element S = Resistance
Q' = Holding coil

position by the mechanical bias. A fault on the feeder upsets the balance, and causes operation.

Directional Balance Protection. A more recent pilot wire protective system avoiding the use of balanced current transformers, is the directional balance system. Its principle is illustrated by Fig. 84. At each end of a line section, a directional relay (Q/q) is combined with an excess current, an under-voltage, or an under-impedance relay, and the two directional contacts are connected in series over the pilot wire and the releasing coils. The two directional relays respond in the event of energy flowing away from their respective bus-bars, so that

only the two circuit-breakers protecting the faulty section are tripped. This system is only applicable where the protected section is, under all circumstances, fed from both ends.

In order to make a similar system operative at times when the section is only fed from one end, change-over contacts (a/b* in Fig. 84) are provided in addition to the potential contacts a and b which are actuated by the same excess

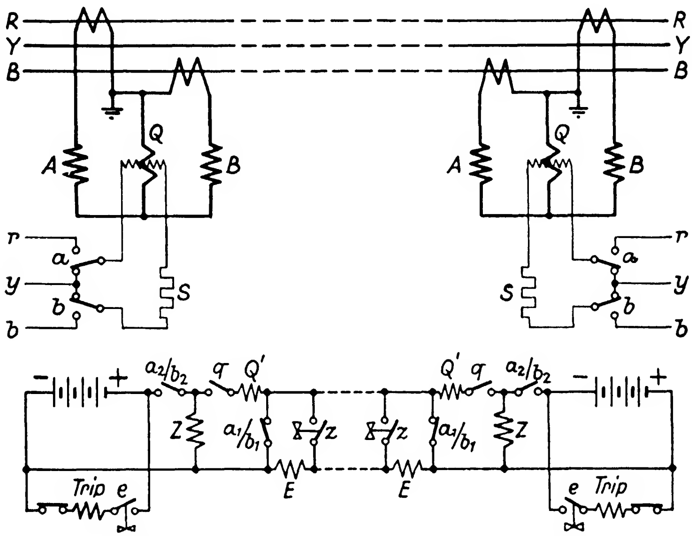


FIG. 85. DIRECTIONAL BALANCE SYSTEM EXTENDING PROTECTION TO THE BUS-BARS

A/a, B/b = Excess-current starting elements	E/e = Tripping element
Q/q = Directional element	S = Resistance
Q' = Holding coil	Z/z = Time relay

current coils (A and B). If a fault occurs within the section the relay at the remote end will not be energized at all, and its contact a/b remains in the position shown, so that the two tripping elements E are energized from one of the batteries.

The system described is still imperfect due to the fact that it leaves the bus-bars unprotected, and also the relays of neighbouring sections do not act so as to back each other up. Hence additional back-up relays of the excess-current type would appear to be necessary; but the difficulty can be overcome by means of simple time relays (Z in Fig. 85), and by providing

* A contact marked thus, a/b, operates when either of the corresponding coils (A or B) is energized.

two separate contacts (a_1/b_1 and a_2/b_2) instead of a change-over contact. In the event of a fault outside the section, the directional relay Q nearest to the fault does not respond and the tripping elements E are not energized; on the other hand both time elements Z are set in motion, and after their time lag has elapsed, one of the elements E trips its circuit-breaker.

This system of selective line protection is distinguished by the use of simple relays and connections. On the other hand, it has the disadvantage (in common with differential protection) of being dependent on pilot wires, whereby its application is limited to short distances. As distance increases this disadvantage becomes prohibitive, unless a connection by carrier current transmission is established over the power line itself.

Systems Without Pilot Wires. For use on extensive networks other means had to be sought to achieve equally selective isolation of a fault, without the use of pilot wires, with a system not excluding protection against faults on, or near to bus-bars, and not requiring an additional emergency protection.

In contrast to open feeders or simple rings, in extensive ring mains or in interconnected networks the excess-current alone cannot be used as a criterion for selective disconnection, as the current may pass through a substation in either direction, dependent upon the position of the fault, wherefore the desirable grading varies.

A combination of excess current time relays and sensitive directional relays is suitable for simple rings with one feeding point. The excess current time relays normally used for this purpose are of the "inverse time lag, with definite minimum time" type. Their releasing time depends on the short-circuit current and may be excessive where the short-circuit current is comparatively low. Also, the highest minimum setting is required just where the fault currents are highest, i.e. nearest to the point of feed. It is, therefore, advisable to use instead excess current relays with two or three definite time steps, a description of which will be found in Chapter VI on pages 92–94.

A more appropriate criterion for a suitable time grading would be the voltage, as this is of course lowest at the fault, and increases towards the power station. Under-voltage relays are, however, non-directional, so that the relays at both sides of bus-bars in a ring main substation would operate simultaneously, thus isolating not only the faulty line, but also the bus-bars of neighbouring substations, and all apparatus

connected to them. If such relays are given a directional bias, so as to operate only when the flow of energy is directed away from the bus-bars, the desired properties are achieved; directional under-voltage relays alone, however, are unable to afford protection against overload, which is often not accompanied by a sufficient drop of voltage. The complete solution of the problem is therefore achieved by using directional under-voltage relays combined with an excess current element.

Distance Protection. The foregoing considerations have led to the design of relays which (*a*) are started under certain fault conditions (*starting element*); (*b*) operate only when the flow of energy is directed away from the bus-bars (*directional element*, which may be combined into one with the time element); and (*c*) operate with selective time characteristics (*time element*).

The higher the fault current and the lower the voltage on the relay terminals, the shorter must the time lag be.

If t denotes the operating time of the relay;
I_f the fault current;
V_f the voltage in a station under fault conditions; and
c a constant,

the relay must operate in accordance with the equation

$$t = c \times (V_f / I_f) \quad . \quad . \quad . \quad (17),$$

where

$$V_f / I_f = Z_f,$$

the impedance of the circuit between the relay and the fault. This "fault impedance" Z_f is proportionate to the distance between relay and fault; therefore, relays of this type are also called *distance relays*. This term comprises *impedance* relays (with a releasing time $t = c \times Z_f$), *reactance* relays (with a releasing time $t = c \times Z_f \sin \phi$), and *resistance* relays ($t = c \times Z_f \cos \phi$).

In the event of a metallic short-circuit, i.e. a fault having no ohmic resistance due to the presence of an arc or from other sources, all three systems would be equally satisfactory. This is practically the case on systems up to about 33 kV and with short-circuit currents exceeding about 100 A. Under such conditions the arc resistance is negligible except, of course, in connection with resistance relays.

Above 33 kV, the influence of the arc resistance becomes noticeable, particularly when the fault current is low, as may be the case during light load periods, when comparatively few

machines are feeding into the transmission system. In this case the operating time of an impedance relay may be unduly increased by say 0·5 or 1 sec. A resistance relay would be entirely unsuitable for such an application, whereas the reactance relay possesses an ideal characteristic, as it eliminates the ohmic component entirely. However, the high cost of reactance relays limits their application. Suitable means are available for the compensation of the additional arc resistance, in connection with impedance relays. The total number of distance relays now actually installed may well approach 50 000.

Performance of Distance Relays under Various Types of Fault

(*a*) *Single-phase Earth* (Fig. 86). This type of fault is the most frequent disturbance occurring in practice. In a system

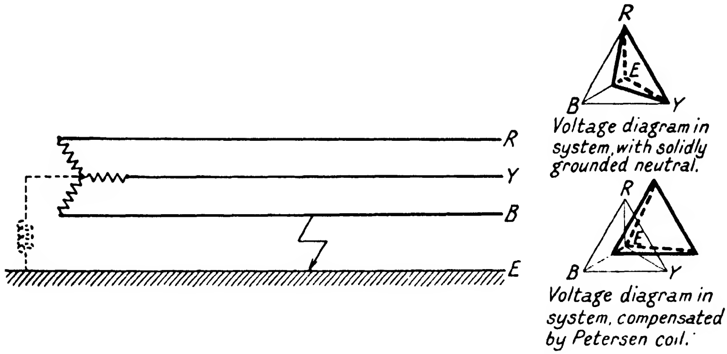


Fig. 86. Single-phase Earth Fault

with the neutral earthed through a Petersen coil it is rendered harmless by the action of the coil which suppresses the fault current, so that distance relays need not and do not respond. If, however, the neutral is solidly earthed, a single-phase earth short-circuits one phase of a star-connected winding, and in consequence the impedance Z_f^1 of the loop consisting of a line conductor, the fault and the earth return back to the relay (neglecting the arc resistance) will be

$$Z_f^1 = Z_l \overset{\wedge}{+} Z_E = Z_l \times (1 + K)^* \quad . \quad . \quad (18)$$

* The symbols $\overset{\wedge}{+}$ and $\overset{\wedge}{-}$ are used to indicate a "vectorial sum" or "vectorial difference."

The corresponding "secondary impedance" is

$$z_f^{\mathrm{I}} = k \times Z_f^{\mathrm{I}} = k \times Z_l \times (1 + K) \quad . \quad . \quad (18a)$$

In these equations,

Z_l denotes the impedance of a line conductor between current transformer and fault, the "phase impedance,"
Z_E the impedance of the earth return,
$K = Z_E/Z_l$, and
k is the ratio of transformation, i.e. the ratio of the current transformer divided by the ratio of the voltage transformer.

With a phase voltage V_{ph}, the current in the faulty loop is

$$J_f^{\mathrm{I}} = V_{ph}/Z_f^{\mathrm{I}} = V_{ph}/[Z_l \times (1 + K)] \quad . \quad (19)$$

and thus a relay connected to phase voltage will record the correct phase impedance (i.e. the value determining the distance) if the current path is energized by $J_f^{\mathrm{I}} \times (1 + K)$.

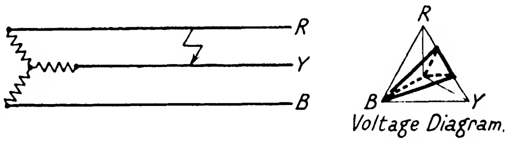


FIG. 87. TWO-PHASE SHORT CIRCUIT

The value of K is difficult to determine; also it is not constant, but subject to fluctuations in accordance with varying conditions of the soil. Unless exceptional accuracy is required it is therefore usual to introduce the following simplification.

The earth resistance at 50 cycles is about 0·05 to 0·1 Ω per mile, and the reactance of the loop conductor-fault-earth is practically equal to that of a loop conductor-fault-conductor. The resulting loop impedance is not much different from that of a loop conductor-fault-conductor. The latter is therefore substituted; in other words it is assumed that $K = 1$ or $Z_l = Z_E$. From this follows—

$$z_f^{\mathrm{I}} \simeq 2 \times k \times Z_l \quad . \quad . \quad . \quad (20)$$

(*b*) *Two-Phase Short* (Fig. 87). The effect of this type of fault is the same whatever the method of earthing the neutral.

The secondary impedance of the loop conductor-fault-conductor is

$$z_f^{\text{II}} = k \times Z_f^{\text{II}} = k \times (V/I) = 2 \times k \times Z_l \quad . \quad (21)$$

The resulting loop impedance is thus practically the same as in the event of a single-phase short.

It will be noted that in this instance the line voltage V (or the corresponding secondary voltage v), must be applied to the voltage system of the relay, instead of the phase voltage V_{ph} (or v_{ph}). The current path carries the line current.

(*c*) *Three-Phase Short* (Fig. 88). In this case the three fault current vectors I_1, I_2, and I_3 have different angular positions,

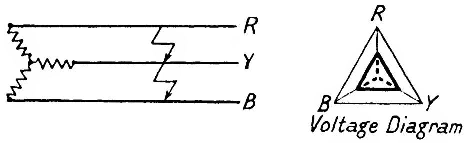


FIG. 88. THREE-PHASE SHORT CIRCUIT

so that the two phase impedances Z_{l_1} and Z_{l_2} of a loop conductor 1-fault-conductor 2, must be added geometrically. The resulting secondary loop impedance

$$z_f^{\text{III}} = k \times (Z_{l_1} \wedge Z_{l_2}) = k \times Z_l \times \sqrt{3} \quad . \quad (22)$$

Owing to the symmetrical nature of a three-phase fault, the fault may be regarded as the star point of the three phase impedances

$$Z_l = V_{ph}/I = V/(I\sqrt{3}) \quad . \quad . \quad (22a)$$

Hence a relay connected to phase voltage and line current records the phase impedance. The same result is obtained with a relay connected to line voltage and the resulting current of delta-connected current transformers (equation 22*a*). In order to measure the total loop impedance (equation 22) the relay must be connected in the same way as indicated above for a two-phase fault, namely to line voltage and line current. In this case, as a comparison of equations (22) and (21) will show, a relay with a given straight-line characteristic will have a slightly shorter releasing time with a three-phase fault than with a two-phase fault.

(*d*) *Double Earth Faults*. If two earth faults occur simultaneously, fault currents and fault impedances are not the

same as in the case of a two-phase short, even if the two faults are close together. There are three fault loops, one of which comprises the two faulty conductors and the ground section between the two faults. Therefore, relays may be connected in the same way as for two-phase shorts, though some correction may be necessary.*

On the other hand, the secondary impedance of each loop conductor-one of the faults-earth return, is similar to that in the case of a single earth. Hence, relays may also be connected between phase and earth.

If a more accurate grading is desired, this may be achieved by introducing the earth current.† The relay will record correct distance, if energized by phase voltage to earth and the current $I \overset{\wedge}{+} KI_E$ or by line voltage and the current $I \overset{\wedge}{-} \frac{1}{3}I_E$. The summation of the two currents can be carried out by two separate current coils in the relay, or with the help of an intermediate summation transformer.

In a system with insulated neutral and earth current compensation through a Petersen coil, it is desirable to make use of its inherent ability to continue operation for some time with one conductor earthed; hence, of two earth faults occurring simultaneously on different phases and in different line sections, only one must be cleared, leaving alive the line section affected by the second fault, and further all sections between the two faults and all substation bus-bars. In order to achieve discrimination between the two earth faults, even if they should be fairly close together, it is necessary to introduce an arbitrary transfer system, so that only one of the two faulty earth loops is connected to a relay, and the second is not dealt with at all.

(*e*) *Power Oscillations*. Though the distance protective system, like any other selective system, is primarily devised with a view to isolating a fault, its performance must also be studied when subjected to power oscillations, such as occur when the stability of a system fed from several generating stations is upset. In this event heavy irregularities of voltage and current may occur in any section not affected by a fault; these irregularities may become such as to cause the undesired

* For the purpose of a full analysis of unsymmetrical faults the method of symmetrical sequence components is usefully applied. See *The Electrician*, 1934, pp. 95, 241, 433, 573, 797; 1935, pp. 183, 341, 599 (G. A. Robertson); or *Symmetrical Components*, by Wagner and Evans (McGraw Hill).

† See Bibliography Nos. 38 and 43.

isolation of healthy sections. Therefore it is, as a rule, necessary to prevent relay operation in case of through faults. An exception is made in the case of a line connecting two generating stations which have fallen out of synchronism. The general requirements of a protective system under conditions of instability are, therefore, that no healthy sections shall be cut out, so that the generating stations are given an opportunity of pulling into synchronism; but that, after a certain

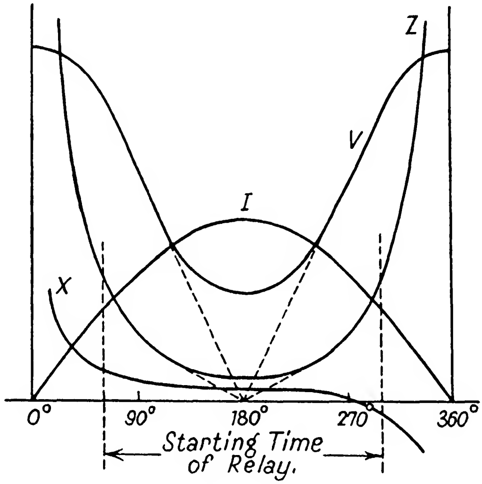


FIG. 89. VARIATION WITH TIME OF VOLTAGE (V), CURRENT (I), IMPEDANCE (Z) AND REACTANCE (X) AT ONE POINT OF A COUPLING LINE

time has elapsed a circuit-breaker, preferably a predetermined coupling circuit-breaker, shall separate the power stations from each other if they remain out of step, or if there is no reasonable chance of synchronism being re-established.

Fig. 89 illustrates one full cycle of the fluctuation of current, voltage, impedance and reactance, measured at any point of a line coupling together two power stations generating at different frequencies. The duration of the cycle is determined by the difference of the two frequencies and, in practice, amounts to between 0·2 and 2 sec. Any relay in the run of the line will operate the appropriate circuit-breaker, if its time setting is smaller than the time during which its determining value (current, voltage, impedance or reactance) remains beyond the releasing limit.

Thus, for example, an impedance relay will operate if the impedance drops sufficiently low for a sufficient length of time. Fig. 90 shows the local distribution of impedance over the whole length of the line for seven typical instants (marked 1 to 7, 45° apart) during one full cycle; it appears that there is one point at which the impedance is lowest; thus the relay nearest to this point will trip its breaker (if operation occurs at all) in a shorter time than all the other relays, thereby

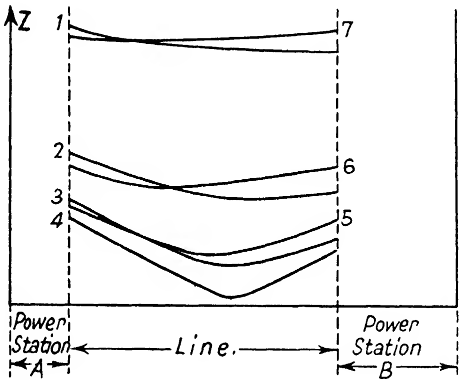


FIG. 90. LOCAL DISTRIBUTION OF IMPEDANCE OVER A COUPLING LINE AT VARIOUS INSTANTS (1–7) DURING ONE FULL CYCLE

isolating the two power stations from each other. This proves that the impedance relay, by suitable settings of its starting element, can be made to comply (though perhaps not under all circumstances) with the requirements defined above.

Conditions are less favourable with reactance relays. Here the point where the reactance is nil travels along the line, and may cause the tripping of a number of circuit-breakers. Means are available, however, for achieving satisfactory results.*

PRINCIPLE OF DESIGN OF DISTANCE RELAYS. In accordance with the principle of operation explained above (p. 108), a distance relay consists of three main parts, viz.—

(*a*) *The Starting Element*, which responds when certain fault conditions prevail on the protected line section, and causes the immediate starting, by electrical or mechanical means, of the time element and also of the directional element.

* See Bibliography Nos. 37, 42, 46.

There are three distinct ways of determining the correct moment for a distance relay to be set in motion. The first is by means of an excess current element, with a setting between one and two times the normal line current. This method is the simplest, and is perfectly adequate, as long as it is impossible for the short-circuit current to be lower than the normal operating current. This, is, as a rule, the case in overhead or underground networks up to 33 kV. In under-

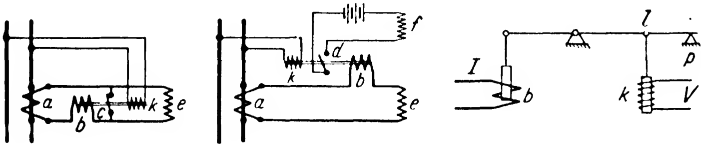


FIG. 91. VARIOUS PRINCIPLES OF CONNECTING UNDER-IMPEDANCE STARTING ELEMENT

a = Current transformer
b = Current coil of starting element
c = Normally-on contact
d = Normally-off contact
e = Current coil of distance/time element
f = Time element coil
k = Voltage coil of starting element
l = Balanced beam
p = Stop

ground cable systems the thermal capacity is mainly the determining factor, so that the simple excess-current element is entirely suitable for such installations. Where the number and size of machines connected to a system vary between wide limits, and the short-circuit current at times of light load, when only one or few machines are connected, is often lower than the normal load current, the excess-current starting element is not suitable.

Secondly, an under-voltage relay may be used as a starting element. This is frequently combined with an excess-current relay which becomes operative in the event of an overload on the line, or if for some other reason the voltage is maintained at a value above the setting of the under-voltage relay.

The third alternative is a starting element of the under-impedance type. This consists of a current coil and a voltage coil, the combined action of which sets the time element in motion under certain fault conditions. The two coils may for instance act on a mutual mechanical system, their respective forces (see Fig. 91) opposing each other. Under normal operating conditions, the action of the voltage coil retains the mutual shaft or lever in its normal position. As soon as the force of the current coil prevails, i.e. when the element records a low impedance, the shaft or lever is moved into releasing

position. This occurs in the event of a fault, or of a considerable overload, in this latter case also when the voltage is at its full value. Fig. 92 illustrates the secondary impedance of a typical line (relating to secondary currents of 5 A and a secondary voltage of 110 V) under normal operating conditions (curve a), and under a short circuit (curve b).

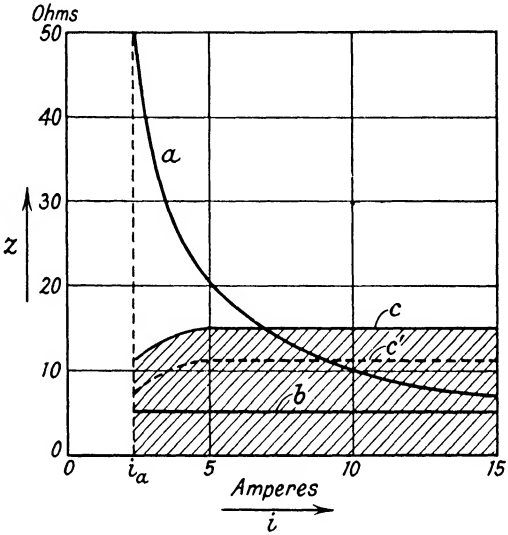


FIG. 92. IMPEDANCE CHARACTERISTICS OF A TYPICAL TRANSMISSION LINE

a = Line impedance at full voltage
b = Line impedance under short-circuit conditions
c = Straight-line characteristic of under-impedance starting element
c' = Alternative characteristic

The short-circuit impedance (curve b) is only determined by the distance from the fault, and is independent of the magnitude of current. During the transitional period, in the event of a fault, the line impedance drops from a point on curve a, to a point on curve b. Curve c shows a typical characteristic of an under-impedance starting element designed on the lines of Fig. 91. This characteristic follows the equation

$$c_1v^2 - c_2i^2 + k = 0 \quad . \quad . \quad . \quad (23),$$

or

$$z = v/i = \sqrt{(c_2/c_1 - k/c_1i^2)} \quad . \quad . \quad (23a),$$

where v is the secondary voltage of potential transformers, i the secondary current of current transformers, c_1 and c_2

are constants, and k is a constant additional force exerted by a spring or weight on the mutual shaft or lever. The influence of the term k/c_1i^2 is only felt with low currents.

When the line impedance falls below curve c, i.e. within the shaded portion of Fig. 92, the starting element will operate. With a characteristic such as the one shown in curve c, the

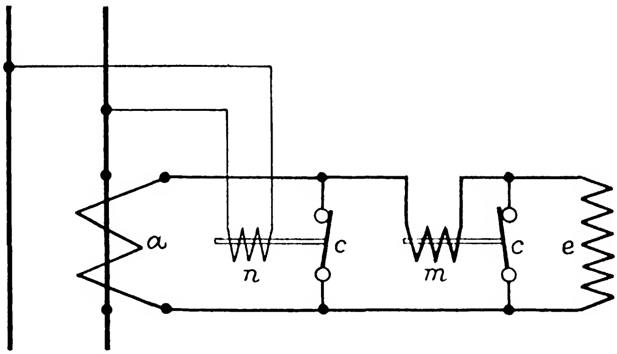


FIG. 93. UNDER-IMPEDANCE STARTING ELEMENT WITH HYPERBOLIC CHARACTERISTIC

(See Fig. 94)

a = Current transformer
c = Contacts
e = Current path of distance relay
m = Current coil
n = Voltage coil

lowest starting current is about 40 per cent (2 A secondary current), but this minimum current may be varied by means of an adjustable spring tending to hold the starting element in its normal position. This is of great importance in systems having temporarily low short-circuit currents.

An under-impedance starting characteristic similar to curve c of Fig. 92, which is essentially a horizontal straight line, will be found suitable where the operation of relays is also desired in case of slight overload on any part of the system. Frequently, however, this is not desirable, particularly where twin circuits are to be protected. In this case the setting of curve c may be reduced to a lower value (curve c'), so as to move intersection with curve a to a higher current value. This measure, however, may lead to failure in the event of short-circuits through a high resistance arc or through earth, as the fault impedance may then be above curve c'.

For this reason a different type of under-impedance starting element may often be preferable, whose principle is exemplified by Fig. 93. Current and voltage coils operate two separate

normally-on contacts, both shunt connected with the current coil of the time element. Only when both contacts are open is the relay ready to operate; in this case the voltage element is set to open when the voltage falls below a value v_0 and the current element opens when the current exceeds a value i_0. The resulting characteristic is a hyperbola (Fig. 94) and is similar to that of an under-voltage starting element, with

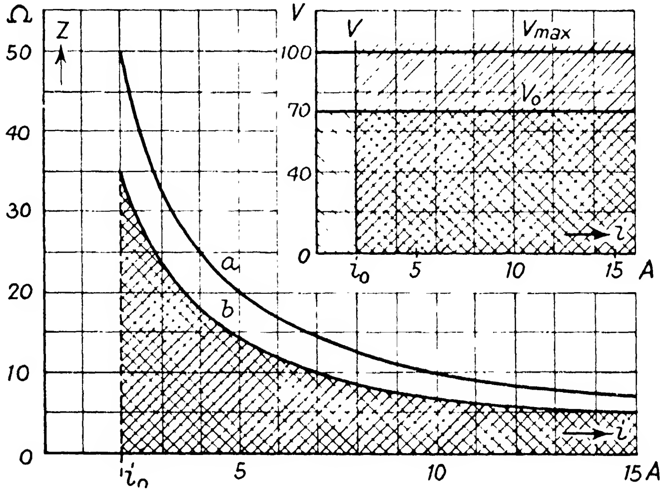


FIG. 94. CHARACTERISTIC CURVE OF UNDER-IMPEDANCE STARTING ELEMENT

(See Fig. 93)

a = Normal working impedance i_0 - Minimum starting current
b = Starting impedance v_0 - Maximum starting voltage

the exception that no operation occurs unless the current value i_0 is exceeded. This type has the disadvantage of being unsuitable for protection against overloads which do not cause an appreciable voltage drop on the relay terminals.

Sometimes the straight line and the hyperbola are usefully combined into a characteristic of the kind shown in Fig. 95. Manifold ways are open to the designer to produce any desired characteristic; which type of starting element is best suited for a particular case depends upon various conditions, as already indicated. A starting element having a characteristic similar to Fig. 95 offers the advantage of being universally applicable, because such a characteristic can always be modified by simple adjustments into one as in Fig. 92 or Fig. 94 or intermediate

It is possible to combine the under-impedance starting element with the impedance/time element, but as this is achieved at the expense of variability of characteristics, it is advisable to use two separate elements, if variable characteristics are aimed at. Any type of starting element may be fitted with change-over or selector contacts, in order to connect the relay to different current and potential circuits, in

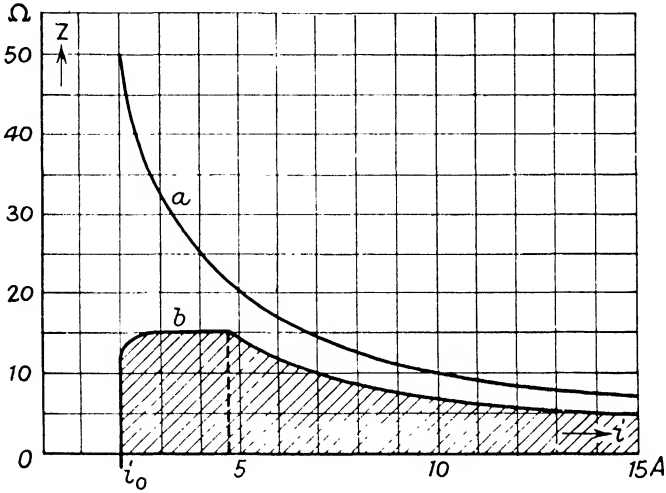


FIG. 95. COMBINED CHARACTERISTIC OF STARTING ELEMENT

a = Normal working impedance i_0 = Minimum starting current
b = Starting impedance

accordance with the requirements of each particular type of fault.

(*b*) *The Directional Element.* Unless the time element itself has directional features, a separate directional element is necessary, except on feeders with open ends, or in other special circumstances. The directional element is built on the wattmeter principle, and may be of the electrodynamic, electromagnetic or induction type. The directional sensitivity must be such that operation is positive even when the line voltage collapses to a fraction of one per cent of its normal value, i.e. when a fault occurs in the immediate neighbourhood. This is essential, as the faulty section only must be disconnected, and under no circumstances must a relay operate unless the energy flow through its current transformers is directed away from the bus-bars, or the voltage is practically nil.

The prevention of release in case of energy flowing towards the bus-bars may be achieved through mechanical or electrical means.

(*c*) *The Time Element.* The principle of distance protection requires that the relay, once set in motion by the starting element, shall discriminate between faults in accordance with their distance from each relay. Hence a time element is required giving a greater delay, the further away the fault has occurred. Let it be assumed, for the time being, that the desirable distance/time characteristic is a straight line, i.e.

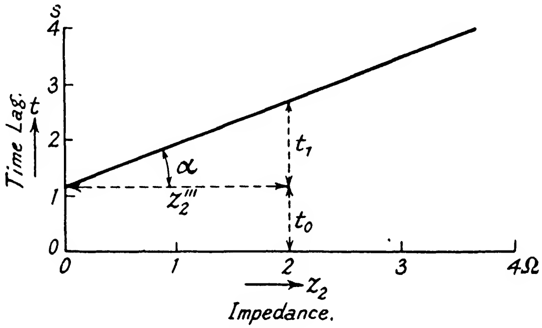


FIG. 96. STRAIGHT LINE CHARACTERISTIC OF DISTANCE/TIME ELEMENT

t_0 = Minimum time lag $\quad t_0 + t_1 = t_0 + z_2''' \tan\alpha$ = Time lag for impedance z_2'''

a time lag increasing in direct proportion with the distance (Fig. 96). Manifold ways are available for achieving this effect. Several well-known designs make use of an induction type disc driven by suitably energized coils, exerting a torque against the action of a spring. A separate voltage element, normally of the attracted armature pattern, retains the releasing contact until the force of the time element exceeds that of the voltage element, when the releasing contact is closed (or opened), and thereby the tripping circuit of the circuit-breaker is actuated. Another very common design consists of a bi-metal strip influenced by the current, which moves a multiple lever system, (5 to 8 in Fig. 97) in such a way, that the time for closing (or opening) the releasing contact (11) is determined by the value of the current, and also by the position of a curved disc fixed to the pointer of a voltmeter.

The minimum time (t_0 in Fig. 96) is partly determined by

technical considerations regarding the network, but mainly by the rupturing capacity of circuit-breakers installed. These are sometimes not suitable for breaking the maximum instantaneous short-circuit current, so that a minimum time lag of

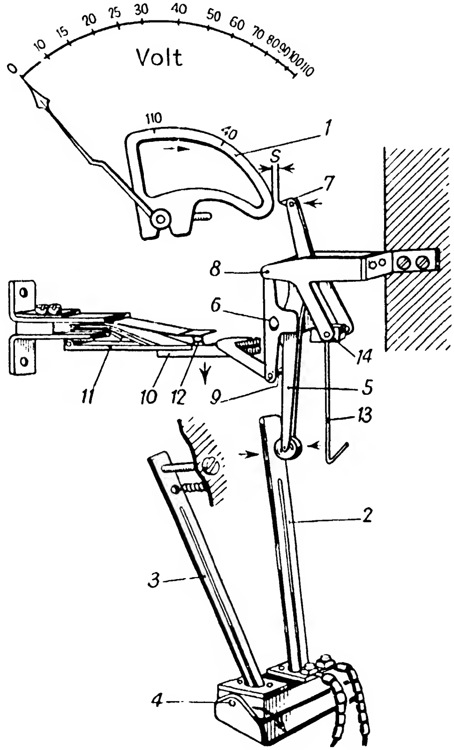


FIG. 97. THERMAL TYPE DISTANCE/TIME ELEMENT

1 = Curve-shaped disc of voltage element
2 = Bimetal strip
3 = Temperature compensation
4 = Shaft carrying the bimetal strips
5–8 = Multiple lever system
9 = Roller
10 = Pawl
11, 12 = Releasing contact
13 = Lever } operated by the directional element
14 = Interlock }

(*A.E.G.*)

0·5 or even 1 sec. is sometimes unavoidable, thus allowing the short-circuit current to decrease before a circuit-breaker is tripped.

Where the rupturing capacity of circuit-breakers is sufficient, the minimum operating time will be made as short as possible. In this case, the minimum time is composed of the

inherent time lag of the starting element and the minimum time of the time element, in all about 0·25 sec. or in the case of some high-speed relays as little as 2 cycles (0·04 sec.).

As regards the time increment, i.e. the difference in operating times between two consecutive relays on the same fault, allowance must be made for the time required by circuit-breakers from the instant of closing (or opening) the tripping circuit, until the actual interruption of the arc. This time is

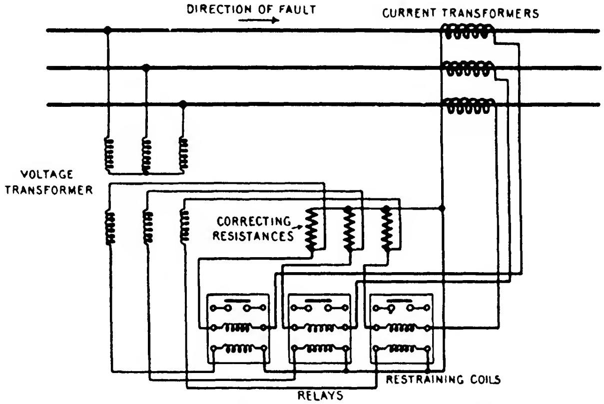


FIG. 98. ELIMINATION OF ARC RESISTANCE
(*Metropolitan-Vickers Electrical Co.*)

0·2 sec. or more; it is shortest in air-blast or oil-blast breakers (see Chapter II).

For use on voltages above 33 kV, the increase of the releasing time due to the arc resistance must be eliminated. This may be effected by means of a compensating resistance connected in series with the current coil, and in series with the coil of the restraining element (Fig. 98). By this or other means the inaccuracy of the releasing time can be greatly reduced.

Considering the tripping time of circuit-breakers, and a certain tolerance on account of inaccuracy, the total time grading between two relays should as a rule not be less than about 0·6 sec.; higher differences, of say 1 sec., are often necessary. Conditions are made more difficult in a network consisting of sections with impedances or reactances differing greatly from one another. In such cases resort may sometimes be made to the utilization of different characteristics on individual relays.

The distance/time characteristics of a well-designed distance relay can be modified in manifold ways, so as to make it suitable for varied operating conditions.

Fig. 99 shows the typical characteristics of an impedance relay. With a secondary current of 20 A, for instance, the full line shows a rise of 0·75 sec. per ohm of the secondary impedance, whereas the dotted line is another setting of the same relay for 1·5 sec. per ohm.

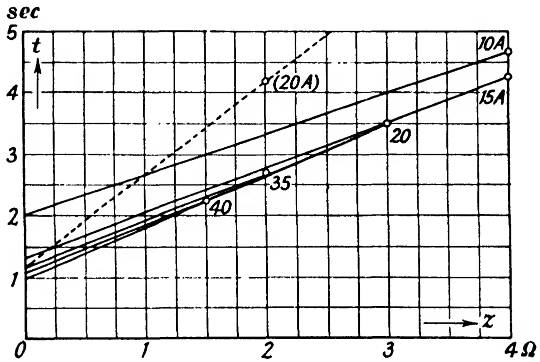


FIG. 99. TYPICAL CHARACTERISTICS OF IMPEDANCE RELAY
The full lines refer to different currents with one setting. The dotted line refers to another setting

HIGH-SPEED DISTANCE PROTECTION*. Often it is altogether impossible with any type of distance relay having a steady characteristic to devise a protective system combining selective operation with sufficiently low time lags, such as are nowadays required with a view to the stability of large power plant. Time lags up to the values mentioned above are, as a rule, permissible from the point of view of protecting machines and transformers, but a time of less than half a second is often sufficient to cause machines or whole stations to fall out of synchronism. Further, they may be excessive with regard to the thermal overload capacity of cables, current transformers, etc.

Provided the existing circuit-breakers are up to their duty, there is no reason why a time lag, in addition to the inherent

* The term "high speed" is here used to distinguish distance relays with stepped characteristic from ordinary distance relays, and does not imply any relation to those "high speed relays" which operate within a time sometimes as short as two half cycles (see pp. 13, 129, 179).

operating time of relays and circuit-breakers, should be introduced. In systems with solidly earthed neutral, earth faults in particular should be disconnected without any loss of time, in order to avoid their developing into a short-circuit across phases.

In all such cases much lower time lags may be required than those obtainable with distance/time elements having a straight-line characteristic. For this purpose, quick-acting distance relays have been developed by several firms. The simplest type is one without a time lag. It is set so as to operate

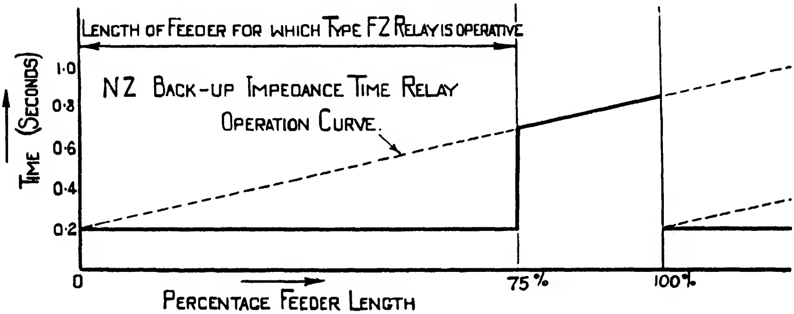


FIG. 100. COMBINED CHARACTERISTIC OF INSTANTANEOUS AND DELAYED DISTANCE RELAYS

(*Metropolitan-Vickers Electrical Co.*)

instantaneously when a certain fault occurs within a certain distance, say 75 per cent or 80 per cent of the feeder section. Another "back-up" relay of the distance/time type becomes operative when the fault lies in the remainder of the feeder section, or when the quick-acting relay fails to operate (see Fig. 100). This simple type of undelayed under-impedance relay is mainly used for protection from earth faults in systems with solidly earthed neutral. Due to the necessity for additional back-up relays, this solution has not found much application.

The same characteristic is obtainable from a combined single relay of the type shown in Fig. 101. In this case the action of the instantaneous step is inverted, i.e. undelayed tripping occurs unless the impedance is high enough to cause the operation of an over-impedance element. This has the advantage that an over-impedance element is a more reliable device than a highly sensitive under-impedance relay. Another

interesting feature of the relay illustrated in Fig. 101 is that it comprises a number of auxiliary selector contacts so that a single relay is made to protect all three phases (see p. 144).

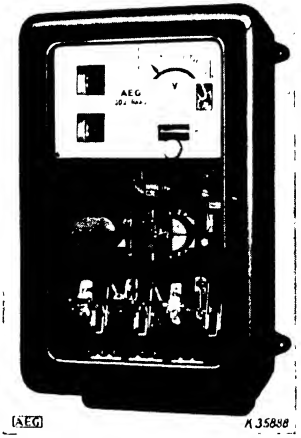


FIG. 101. TYPICAL MODERN HIGH-SPEED DISTANCE RELAY FOR LINES UP TO 33 kV. (*A.E.G.*)

Another type embodying all necessary features is obtained by combining an instantaneous-acting relay with a multi-step time element. Fig. 102 shows a typical line with four stations *a*, *b*, *c* and *d*, and will explain the fundamental idea. A fault occurring within, say, the first 75 per cent or 80 per cent of the nearest line section (*a* to *m*) is cleared in the shortest time. If the distance is greater, a time lag is introduced. If the fault is further away than about the middle of the following section (*n*), this time lag is further increased, as far as the operation of relay *a* is concerned. In case of a fault between *b* and *c*, the relay at *b* will clear the line and relay *a* will act only as a standby.

The principle of operation is illustrated by Fig. 103. *K* is

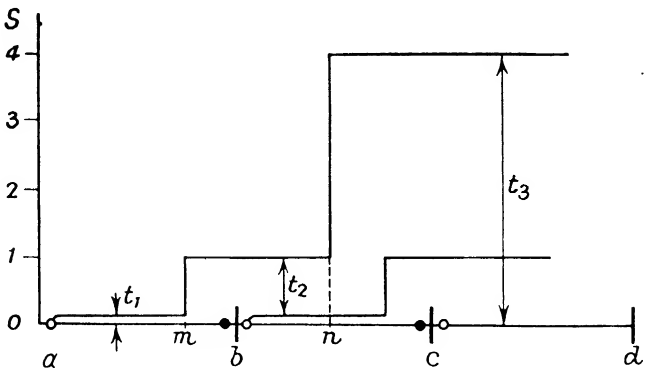


FIG. 102. HIGH-SPEED DISTANCE PROTECTION WITH THREE DEFINITE TIME STEPS

a, b, c, d = Stations
m = Setting of first over-impedance relay in station a.
n = Setting of second over-impedance relay in station a
t_1, t_2, t_3 = Time lags of relay operation

the time element having three steps. With a low impedance, contact k_1 closes the tripping circuit, provided of course the contacts of the starting element A and of the directional element Q are closed. When the impedance is high enough to operate the over-impedance element G (i.e. when the distance

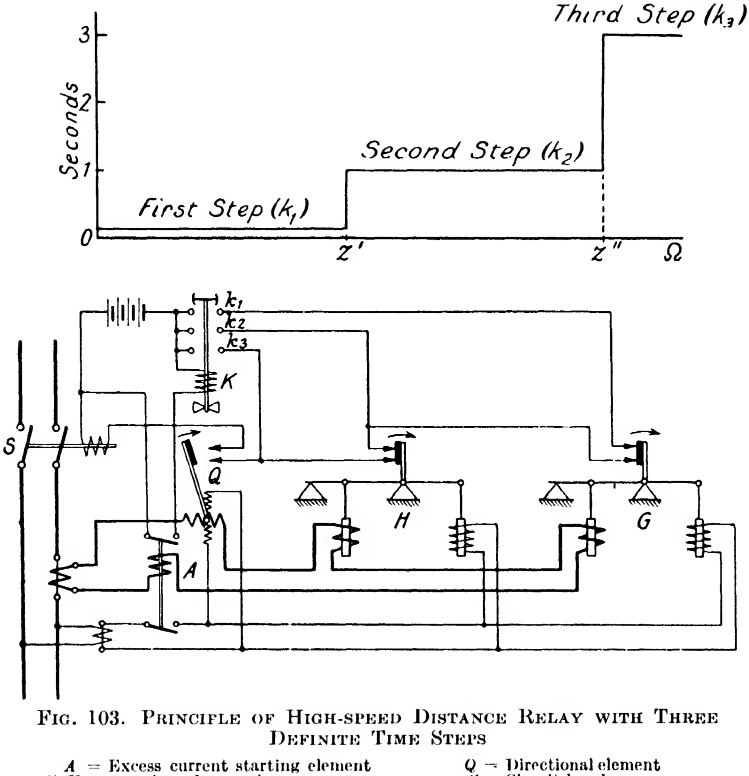


FIG. 103. PRINCIPLE OF HIGH-SPEED DISTANCE RELAY WITH THREE DEFINITE TIME STEPS

A = Excess current starting element
G, H = Over-impedance relays
K = Three-step time element (k_1, k_2, k_3)
Q = Directional element
S = Circuit-breaker
z', z'' = Settings of relays G and H

exceeds 75 per cent or 80 per cent of the length of the first line section), operation cannot occur until the time contact k_2 is closed. Still higher impedances (corresponding to a distance beyond the middle of the second line section) will cause both elements G and H to open their contacts and the circuit-breaker will not be tripped before the last time-contact k_3 has closed. As this third step is only intended for emergency operation in case of the relay or relays nearer the fault

failing, its time lag is set as high as is considered permissible in the particular system. Fig. 104 shows a typical characteristic of a quick-acting distance relay. The design may, of course, be modified in various ways.

While relays as in Figs. 100 to 104 meet the requirements of systems with voltages up to 33 kV, they would not be suitable for higher voltages, owing to the influence of the arc resistance. In this case reactance relays must be used, or if impedance is

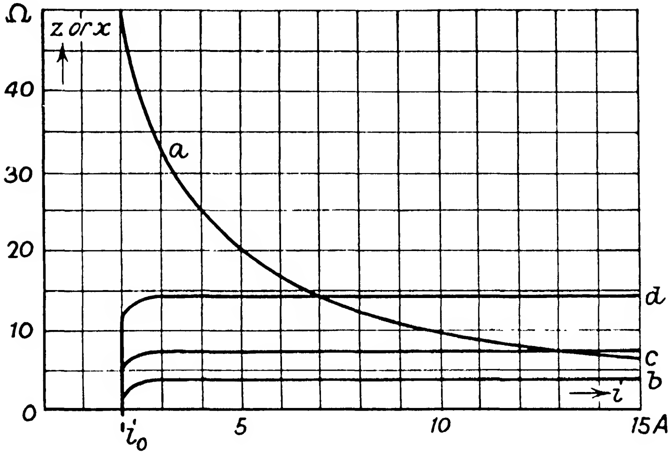


FIG. 104. TYPICAL CHARACTERISTIC OF A THREE-STEP HIGH-SPEED DISTANCE RELAY

a = Normal line impedance (or reactance)
b = Tripping impedance (or reactance), first step
c = Tripping impedance (or reactance), second step
d = Tripping impedance (or reactance) third step

used as a criterion, provision must be made to eliminate the influence of the arc resistance. This is easily achieved, if the releasing time is determined during the first 0·2 sec., i.e. while the arc resistance is low.

In Fig. 105 contact k_4 closes after a definite time of 0·2 sec. In this case the releasing circuit is not connected in series with contacts G and H, but through auxiliary contactors G' and H' with holding-on contacts. Thus, whatever happens in the faulty loop afterwards, no further alteration takes place in the releasing circuit once contactor P has de-energized the voltage coils of elements G and H after 0·2 sec.; except, of course, when the fault disappears altogether, thereby resetting the whole relay to normal. A relay of this

type does not react on subsequent alteration of the type or distance of a fault upon which it has started to operate. The short duration of increased burden also benefits the potential transformers.

A relay of this design is illustrated in Fig. 106. As in Fig. 101, the distance relay is again combined with a number of selector contacts so as to protect all three phases.

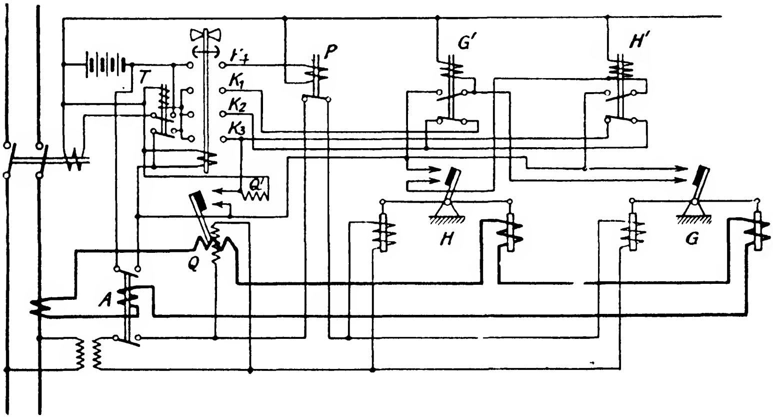


FIG. 105. HIGH-SPEED DISTANCE RELAY FOR HIGHEST VOLTAGES

The operating time is determined within 0·2 seconds and the influence of the arc resistance is thereby eliminated.

(*A.E.G.*)

A = Excess-current starting element
G, *H* = Over-impedance relays
G′, *H′* = Auxiliary relays
K_1–K_4 = Time step contacts
P = Auxiliary relay interrupting the potential circuit after 0·2 sec.
Q = Directional element
Q′ = Holding coil of directional element
T = Tripping relay

An alternative way of eliminating the arc resistance is to make the second and third steps of an impedance relay measure the reactance of the fault circuit.

In the case of Figs. 101 and 105 the distance elements are built on the principle of beam relays. This design is suitable for both impedance and reactance elements. For reactance units, the dynamometer type has many features to commend its application. In one well-known reactance relay the induction dynamometer principle is used, where the current in the moving coil is induced by transformer action. In order to obtain a reactance characteristic, windings are arranged as shown in Fig. 107. The two current windings (*a* and *b*) will give a torque proportional to i^2, whereas current winding

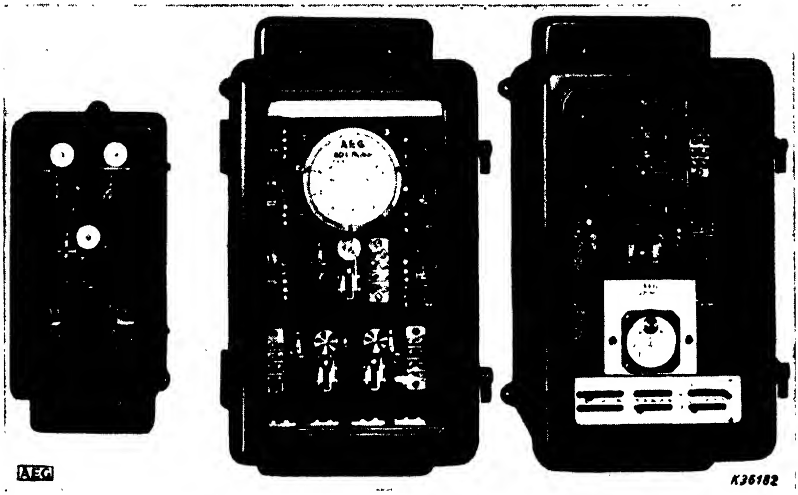


FIG. 106. THREE-STEP HIGH SPEED DISTANCE RELAY FOR HIGHEST VOLTAGES

For solidly earthed neutral, including selector relays.
(*A.E.G.*)

a, and the potential winding c, furnish a torque proportional to $v \times i \times \cos(\phi - \theta)$, where ϕ is the power-factor angle of the protected circuit, and θ is the angle between v and i at which a maximum torque would be obtained. If by means of suitable resistance and reactance in the potential circuit θ is made to be 90°, the second torque becomes equal to $v \times i \times \sin \phi$. The two torques counteract each other, so that the resulting torque is nil if

$$v \times i \times \sin \phi = k \times i^2 \quad (24)$$

The relay closes its contact if

$$(v \times i \times \sin \phi)/i^2 < k \quad (24a),$$

i.e. if the reactance of the circuit falls below a predetermined value. The operating time of this type is only two cycles,

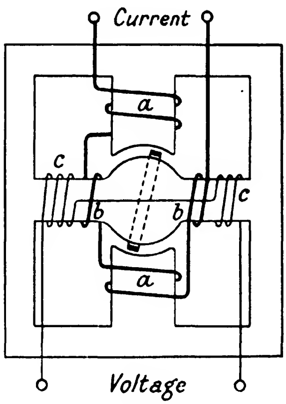


FIG. 107. CONNECTIONS OF A REACTANCE RELAY

a, b = Current windings
c = Potential winding

METHODS OF CONNECTING DISTANCE RELAYS. The internal and external connections of a single-phase distance relay are illustrated in Fig. 108. The starting element *a* is, in this instance, as in all the following diagrams, of the excess current type. Other types may, of course, be substituted where necessary. By the closing of its left-hand contacts, the

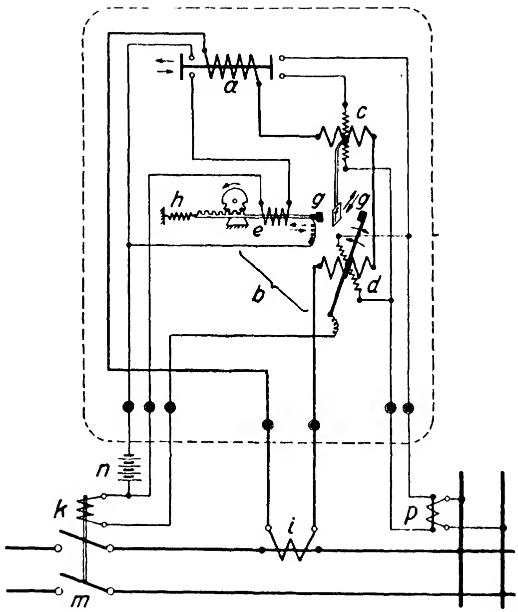


FIG. 108. PRINCIPLE OF IMPEDANCE RELAY CONNECTION

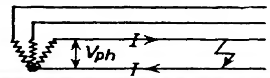
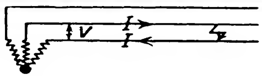
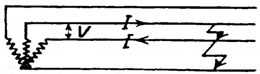
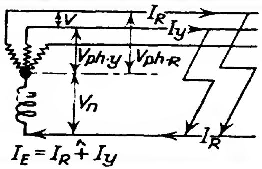
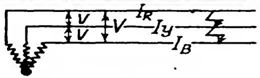
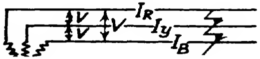
a = Starting element
b = Distance/time element
c = Directional element
d = Impedance meter
e = Time element
f = Insulating plate
g = Contacts
h = Reset spring
i = Current transformer
k = Releasing coil
m = H.T. circuit-breaker
n = Battery
p = Potential transformer

starting element energizes the directional element *c* and the distance/time element *b*. If the flow of energy is directed toward the bus-bars, the insulating plate *f* prevents any further action; if the direction is away from the bus-bars, plate *f* is removed and the contacts *g* close the tripping circuit (in this instance battery operated) after a time dependent on the distance of the fault.

Concerning a three-phase feeder end, it has already been

TABLE V

Connection of Distance Relays for Different Types of Fault

Type of Fault	Neutral	Secondary Fault Impedance	Suitable Connections		
			Voltage Path	Current Path	Time Factor τ
Single-phase Earth 	Solidly earthed	$z^{I} = k \times Z_1 (1 + K)$	V_{ph} V_{ph} $\frac{1}{2} V_{ph}$	$I \hat{+} K \times I_E$ I I	about 1 ,, 2 ,, 1
Two-phase Short  or 	Earthed or insulated	$z^{II} = k \times (V/J) = 2k \times Z_1$	V $\frac{1}{2} V$ V	I I $2I$	2 1 1
Double Earth 	Earthed or insulated	$z^{D} \simeq k \times Z_1 \times (1 + K)$ (exact value depends upon relative location of the two faults)	$V_{ph} \hat{+} V_n$ V $V_{ph} \hat{+} V_n$ V $\frac{V_{ph} \hat{+} V_n}{2}$ $\frac{1}{2} V$	$I \hat{+} K \times I_E$ $I \hat{-} \frac{1}{3} \times I_E$ I I I I	1 2 about 2 ,, 2 ,, 1 ,, 1
Three-phase Short  or 	Earthed or insulated	$z^{III} = k \times \left(\frac{V_{phR}}{I_R} \wedge \frac{V_{phY}}{I_Y} \right)$ $= k \times Z_1 \times \sqrt{3}$	V V_{ph} V V	I I $I \sqrt{3}$ $\frac{I \sqrt{3}}{2}$	$\sqrt{3}$ 1 1 2

shown how the current and voltage paths of distance relays must be connected for correct operation under various types of fault. In Table V the possibilities of connection are recapitulated. For practical application, there are three fundamental methods of energizing each single relay, viz. by—

(1) line current and line voltage; in which case the loop impedance will be recorded;
(2) current and varying voltage, so that either the phase impedance or half the loop impedance is recorded as required;
(3) resulting current and line voltage; in which case relays record the phase impedance.

In each case, further variations are possible; those used in practice are included in Table V. For each connection the corresponding time factor τ is stated, which, if substituted in the equation

$$t' = t_0 + c \times \tau \times Z_l \times f(\phi) \quad (25),$$

gives the resulting time lag.

The constant $c = k \times (t/z)$ is represented by $k \times tg\alpha$ in the relay characteristic (Fig. 96). The term $f(\phi)$ depends on the type of relay and is

$f(\phi) = 1$ for impedance relays,
$f(\phi) = \sin\phi$ for reactance relays,
$f(\phi) = \cos\phi$ for resistance relays.

The original method of distance protection was by means of one relay in each phase. In view of the comparatively high cost of relays a desire was soon felt to reduce their number, and methods were developed using two relays or even only one per set, in connection with automatic transfer relays, leaving it to the latter to assign the requisite phases of voltage and current to the various relay windings.

(*a*) *Connections Using Three Relays*—

(1) *Line Current and Line Voltage.* In Fig. 109, illustrating the principle, current and potential transformers are omitted for reasons of simplicity. Great importance attaches to a correct selection of phases. As may be seen from Fig. 109, relay *a* is energized by the current in *R*, and by the line voltage between *R* and *B*. The current is, therefore, 30° leading when the p.f. is unity, i.e. when I_R is in phase with the phase

voltage V_R. This leading current is desirable in order to achieve directional sensitivity under all circumstances, even when the current I_R lags behind the voltage V_R by about 90°.

In the event of a two-phase short-circuit, as has been shown before (p. 110 and Table V), the acting voltage is the line voltage, so that in this case the fault current is in phase with the line voltage. With a three-phase short, however, the short-circuit current is caused by, and is therefore in phase with, the phase voltage, always assuming unity power factor.

Relays connected as in Fig. 109 will have a somewhat longer time lag with a two-phase fault than with a three-phase

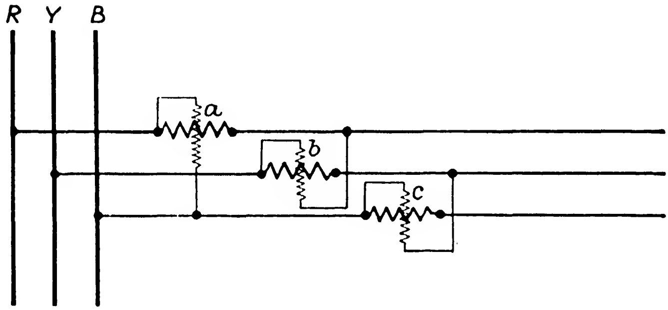


FIG. 109. FIRST FUNDAMENTAL CONNECTION OF THREE DISTANCE RELAYS

Each relay is on line current and line voltage.
a, b, c = Distance relays

fault occurring at the same distance. The value of τ for substitution in equation (25) is $\tau^{\text{III}} = \sqrt{3}$ for a three-phase fault and $\tau^{\text{II}} = 2$ for a two-phase fault.

Another difference in the performance, under two- or three-phase faults, of distance relays connected in accordance with Fig. 109, is that a two-phase fault is only dealt with correctly by one of three relays, whereas a three-phase fault causes all three relays to operate simultaneously.

The connection shown in Fig. 109 is not suitable for dealing with single earth faults on a system with solidly earthed neutral, since in the event of one phase, say R, being earthed, relay a would be energized by the voltage between R and B, i.e. approximately the voltage of a sound phase (B); thus the relay would operate with a very great time lag, if at all.

(2) *Line Current and Varying Voltage.* This principle is illustrated by Fig. 110. With a two-phase fault, only two of

the three starting elements d energize their respective impedance/time elements, so that the voltage path of each relay is on half the line voltage. In the event of a three-phase fault, all three starting elements close their contacts, and the phase voltage is applied to each voltage path. Hence, the time factor will be $\tau^{III} = 1$ for the three-phase fault, and $\tau^{II} = 1$ for the two-phase fault, i.e. the same for both kinds of short-circuits.

It may also be considered an advantage that with this connection two relays operate with correct time lag in the

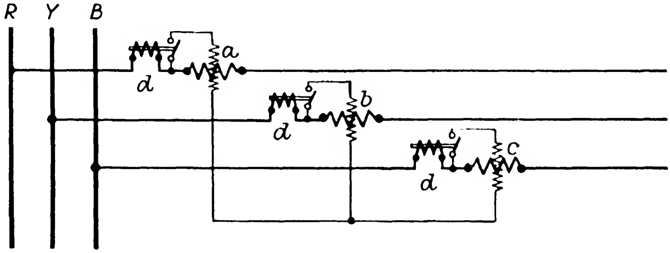


Fig. 110. Second Fundamental Connection of Three Distance Relays

Each relay is on line current and on a voltage varying according to the type of fault.
a, b, c = Distance relays d = Starting elements

event of a two-phase fault. Again a three-phase fault influences all three relays alike.

If the star-point of the three secondary potential paths is earthed, a system as in Fig. 110 can be made suitable for use against single earth faults. In this case the starting element of the affected phases will respond, whereby the appropriate voltage path will be put on phase voltage. Hence the relay will record about twice the phase impedance (see Table V), with a resulting time factor of $\tau^{I} \simeq 2$. This modified connection, however, would be unsuitable for two-phase short circuits.

(3) *Resulting Currents and Line Voltage.* As shown in Fig. 111, the three current transformer secondaries are delta connected, whereas the current paths of relays are star connected. Potential paths are in delta. In the event of a three-phase fault, all three relays are energized by the resulting current of two phases and by line voltage, so that they record the phase impedance (or reactance, etc.); hence $\tau^{III} = 1$.

In the event of a two-phase fault, one of three relays obtains

twice the fault current; the same relay is on the voltage between the faulty phases. Thus it records half the loop impedance, and $\tau^{II} = 1$.

The result is that this connection also leads to equal releasing times for both kinds of short-circuits, but in the event of a two-phase fault only one of the three relays will operate with the correct time lag.

With regard to single earth faults, a connection as shown in Fig. 111 is not suitable for the same reasons as given before under (1) with reference to Fig. 109.

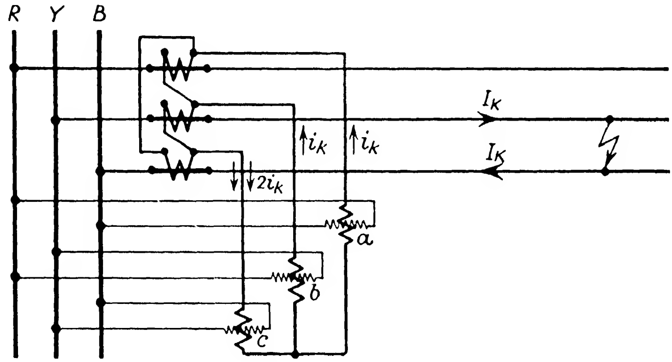


FIG. 111. THIRD FUNDAMENTAL CONNECTION OF THREE DISTANCE RELAYS

Each relay is energized by the resulting current of delta-connected current transformers, and by line voltage. The current as shown refers to a two-phase fault.

a, b, c = Distance relays　　i_k = Secondary fault current
I_k = Primary fault current

(4) *Combined Connections.* Three different connections were given above, each of which fully suffice for the protection of a three-phase system against short-circuits, but not against earth faults. If, however, the neutral is earthed solidly or through a resistance, i.e. if single-phase faults are not rendered harmless by a Petersen coil or equivalent device, the only connection applicable is the one shown in Fig. 110, modified by earthing the star-point of the three potential paths. This connection is, however, not suitable against two-phase short circuits. It is an essential requirement, particularly in the case of high-speed distance protection, that the releasing time shall depend solely upon the distance, and not be different for various types of fault. This means that in an ideal system the time factor must be the same for all kinds of fault. For this purpose, any

of the fundamental connections using three relays can be amplified by the addition of transfer or selector contacts, controlled by the starting elements themselves, or by separate transfer relays which adjust the connections to the type of fault. Of course, it is necessary to make sure that the distance/time element does not act before all the selector relays that should operate have done so; in other words, the minimum operating time must be slightly longer than it would be if no transfer contacts were applied. Transfer contacts in the

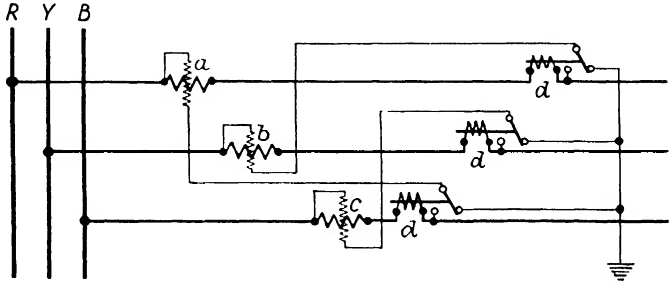


FIG. 112. COMBINED CONNECTION WITH TRANSFER CONTACTS ON THE STARTING ELEMENTS

a, *b*, *c* = Distance relays *d* = Starting elements with transfer contacts

current path must be so designed that the circuit is not interrupted during their operation. All transfer contacts must be maintained with due care, if good results are to be obtained.

Fig. 112 shows an example with transfer contacts on the starting elements themselves.

The three voltage coils are normally at phase voltage. In the event of a three-phase fault, all three voltage coils are transferred to line voltage (thus establishing connections as in Fig. 109) and the time factor is $\tau^{\text{III}} = \sqrt{3}$.

In the event of a two-phase short-circuit, only one of the two relays carrying short-circuit current is transferred to line voltage. This is due to the fact that each starting element controls the voltage path of the relay in the following, and not in its own phase. The time factor is then $\tau^{\text{II}} = 2$.

The same applies to a double earth fault in a system protected by a Petersen coil; in this case the releasing times of the two relays carrying fault current will be of approximately the same value, since, under average conditions, the voltage to earth in any of the faulty phases is, as a rule, approximately equal

to the line voltage between the two faulty conductors. Therefore, the system indicated needs further modification, if only one of two simultaneous earth faults are to be disconnected, which is desirable in a system protected by a Petersen coil (see p. 112).

A single earth fault in a system with solidly earthed neutral is dealt with by line current and phase voltage as desired, with a time factor of $\tau^{\mathrm{I}} = 2$.

Another simple method of providing protection both against short-circuits and earth faults, is illustrated in Fig.

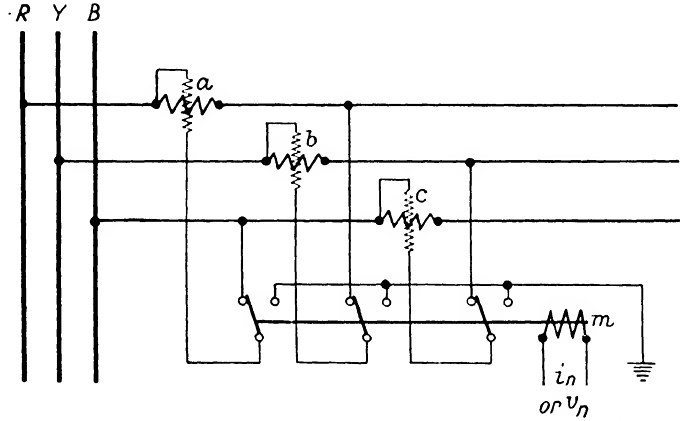


FIG. 113. COMBINED CONNECTION WITH TRANSFER RELAY

a, b, c = Distance relays *m* = Transfer relay operated by neutral current (i_n) or neutral potential (v_n)

113; this is another modification of the first fundamental connection (Fig. 109).

A transfer relay *m* is energized by the residual current in the mutual return of the three current transformers (see Fig. 114(*a*)), or, alternatively, by the voltage between neutral and earth (Fig. 114 (*b*)). In any case, the voltage path of the relays is supplied with line voltage in the event of any symmetrical fault (i.e. two- or three-phase short-circuit). If, due to a single- or two-phase earth fault, a heavy out-of-balance current (or neutral potential) energizes the coil *m*, the three transfer contacts put the relays on phase voltage. The effect is expressed by the resulting time factors—

for a three-phase fault $\tau^{\mathrm{III}} = \sqrt{3}$;
for a two-phase fault $\tau^{\mathrm{II}} = 2$;
for a single or double earth fault $\tau^{\mathrm{I}} \simeq 2$.

In a similar way the second fundamental connection (Fig. 110) can be modified by the addition of a transfer relay *m*,

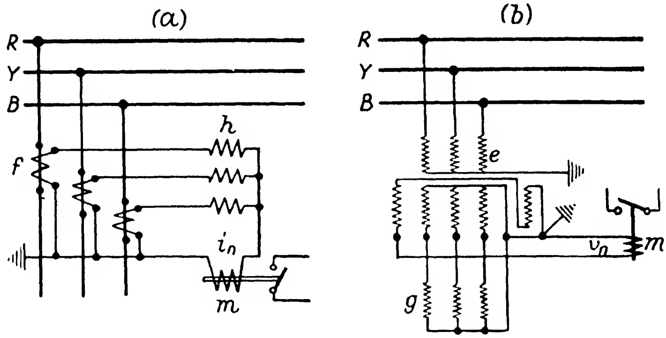


FIG. 114. CONNECTIONS OF TRANSFER RELAY
(*a*) for neutral current, (*b*) for neutral potential.

e = Five limb potential transformer
f = Current transformers
g = Voltage path of distance relays
h = Current path of distance relays
m = Transfer relay operated by neutral current (i_n) or neutral potential (v_n)

which closes the earth circuit in the event of an unsymmetrical fault. In this case the resulting time factors would be $\tau^{III} = \tau^{II} = 1$, but $\tau^{I} = 2$. In order to reduce the latter, an

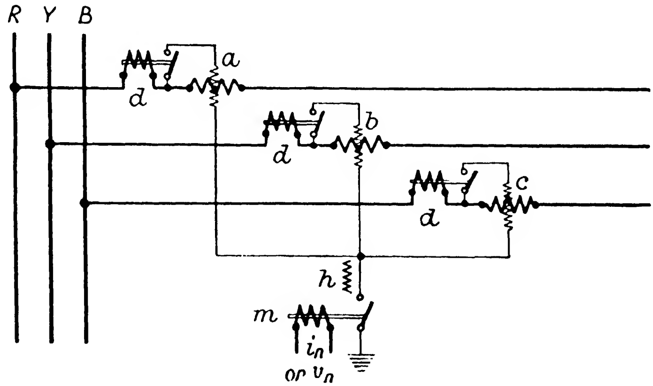


FIG. 115. COMBINED CONNECTION WITH TRANSFER RELAY

a, *b*, *c* = Distance relays
d = Starting elements
h = Series impedance (alternative)
m = Transfer relay operated by neutral current (i_n) or neutral potential (v_n)

impedance *h* may be connected in series, so that the voltage supplied to the relays is halved and τ^{I} becomes 1. (Fig. 115.)

It has been mentioned before and will be shown in detail

further below, that adequate protection can also be afforded by means of two relays or even by one only. If a connection using three relays is to be superior, it ought to be such that with any type of fault, except of course in the case of a single phase fault, two or three relays of one set operate with correct time lag, so that should one of them fail, another one brings about the correct tripping of the circuit-breaker. This is accomplished by a modification of the connections of Fig. 111, as indicated in Fig. 116. The current in each relay is

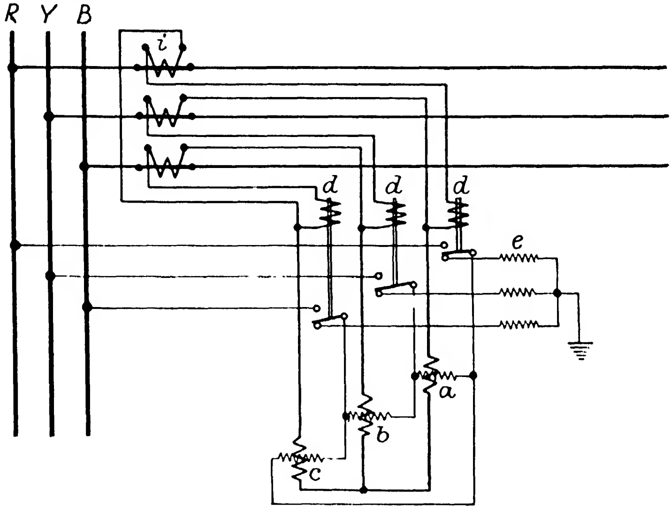


FIG. 116. COMBINED CONNECTION WITHOUT TRANSFER RELAY

a, b, c = Distance relays
d = Starting relays
e = Earthing impedance of potential circuit
i = Current transformers

again the resulting current of two phases. A three-phase fault puts all three voltage paths on line voltage. A two-phase fault causes two transfer relays to operate, so that one distance relay is on line voltage; its current winding carries twice the fault current. The two other relays are each on half-line voltage and on single fault current. Hence, all three relays operate practically with the same time lag.

In the event of single faults to earth, one of the three transfer relays operates, and thereby puts the two distance relays carrying the fault current on half-phase voltage. Hence, the total time lag is the same as for short-circuits, viz—

$$t^{\text{I}} = t^{\text{II}} = t^{\text{III}} = t_0 + k \,.\, Z_l \,.\, f\,(\phi).$$

Regarding earth faults, it has been assumed in all connections so far discussed that the impedance of the earth return equals that of a conductor. Where greater accuracy is required, or where the earth impedance differs greatly from that of a conductor, connections as in Figs. 117 or 118 may be applied. These connections are actually used on systems with solidly earthed neutral.

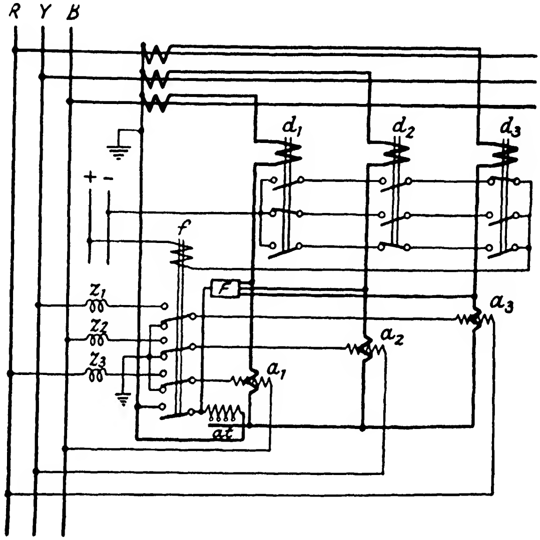


FIG. 117. COMBINED CONNECTION WITH EARTH IMPEDANCE CORRECTION

a_1, a_2, a_3 = Distance relays
at = Auto-transformer
d_1, d_2, d_3 = Starting elements
f = Transfer relay
F = Current filter
Z_1, Z_2, Z_3 = Series impedances

In Fig. 117 the relays a_1, a_2, a_3 are normally on phase voltage, so that three-phase faults are cleared with $\tau^{III} = 1$; a two-phase short-circuit causes the transfer relay f to operate. With two relays on line voltage (halved by the series impedances Z_1, Z_2 Z_3,) and line current, τ^{II} also equals 1; a single earth fault does not affect the transfer relay. The distance relay on the faulty phase is energized by phase voltage and line current, increased by the amount added through a current filter F by means of a tapped auto-transformer *at*. The current can so be adjusted so that $\tau^{I} = 1$.

With the same adjustment the current through each of the two responding relays in the event of a two-phase earth

fault will be about $(I \mathrel{\hat{=}} \frac{1}{3} I_E)$ with half line voltage, whereby $\tau^D = 1$ (see Table V).

Alternatively, the current contacts on the transfer relay can be eliminated by providing an additional selector relay in the residual current circuit, with contacts in parallel with the group of contacts already shown in Fig. 117.

The connection shown in Fig. 118 is similar to that of Fig.

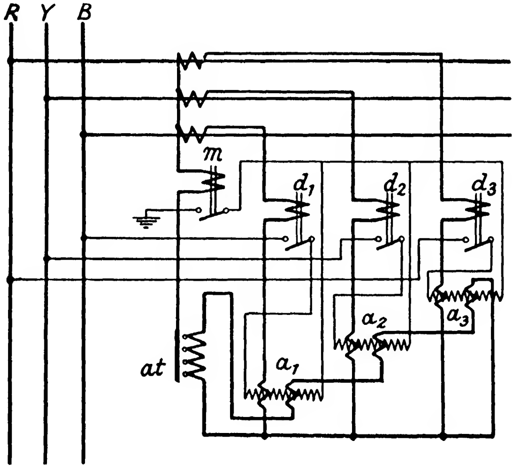


FIG. 118. COMBINED CONNECTION WITH EARTH IMPEDANCE CORRECTION

a_1, a_2, a_3 = Distance relays with two separate current coils
at = Auto-transformer
d_1, d_2, d_3 = Starting relays
m = Transfer relay

115; a second current winding is added on each relay, which is energized by an adjustable portion of the residual current in the earth return, $K \times I_E$. Hence, in the event of single or two-phase earth faults, the respective relays are energized by phase voltage, and by $(I \mathrel{\hat{=}} K \times I_E)$, so that τ^I and τ^D, like τ^{II} and τ^{III}, are 1.

(*b*) *Connections using two Relays.* If one of the three relays shown in Fig. 109 is omitted, the two remaining relays will operate correctly in the event of a three-phase fault; but their action will be somewhat irregular under two-phase fault conditions, as it may happen that both relays are supplied with voltages between a faulty and the healthy conductor. Therefore, the system is not suitable for dealing with two-phase faults, and may only be applied in underground medium voltage cable networks where three-phase faults predominate.

A modification making the system generally applicable is shown in Fig. 119. Transfer contacts *c* and *d* are operated by the starting elements (*b* and *b′*) or by separate transfer relays, so that in any case at least one of the two relays is energized by the fault current and the voltage between the two faulty conductors. Alternatively, transfer contacts may be provided in the current paths.

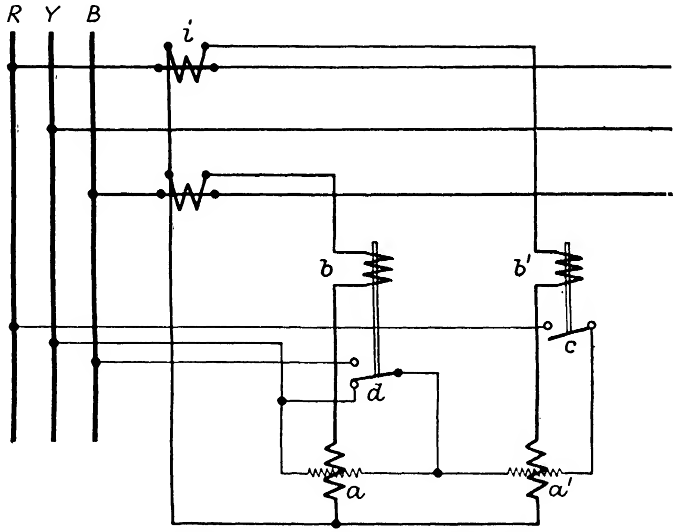


FIG. 119. EXAMPLE OF CONNECTION USING TWO RELAYS

For phase-to-phase faults only.

a, *a′* = Distance relays *c*, *d* = Transfer contacts
b, *b′* = Starting relays *i* = Current transformers

The resulting time factors are $\tau^{\text{III}} = \sqrt{3}$ and $\tau^{\text{II}} = 2$.

The connection is not suitable for dealing with single earth faults, or for the selective disconnection of one earth in the event of a double earth fault, unless three current transformers and transfer contacts in the current circuit are used.

The second and third fundamental connections as in Figs. 110 and 111, may also be modified by the omission of one of the relays; this is again made possible by introducing transfer contacts. Such an arrangement (with a resulting time factor of 1) is rather elaborate, without having any advantage over a single relay system; it has, therefore, found little practical application.

Combined connections with two relays are sometimes used in systems compensated by a Petersen coil, where, in the event of a two-phase earth fault, one fault only should be disconnected. An example is shown in Fig. 120. With a three-phase short all three starting elements (d) respond; the two relays a and b are energized by phase voltage and line current, and $\tau^{III} = 1$. A two-phase short-circuit between phases R and B causes the

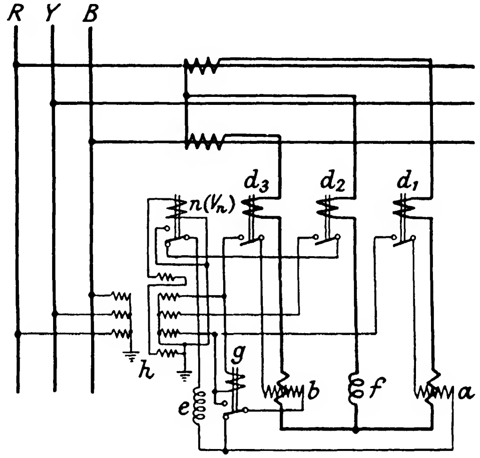


FIG. 120. EXAMPLE OF CONNECTION USING TWO RELAYS, FOR ALL TYPES OF FAULT

a, b = Distance relays
d_1, d_2, d_3 = Starting elements
e, f = Compensating impedances
g = Under-voltage relay
h = Five-limb potential transformer
n = Unbalance relay

starting elements d_1 and d_3 to operate, so that each relay is energized by half the line voltage, and line current; thus $\tau^{II} = 1$. In the event of a short between R (or B) and Y, only one of the two relays (a or b) is energized and operates with the same time factor $\tau^{II} = 1$.

Two simultaneous earth faults, in phases R and B cause the operation of d_1, d_3, g and n. Thus relay b is on full-line voltage and line current ($\tau = 2\sqrt{3}$), whereas relay a is on half the phase voltage to earth (not to neutral) and line current ($\tau = 1$), and therefore operates with approximately the same time lag as that occurring under two-phase short-circuits.

A double earth fault in phases R (or B) and Y causes the operation of d_1 (or d_3), d_2 and n, and is cleared by relay a (or b) on $\frac{1}{2}V_{ph}$ (to earth) and I, with a time factor of 1.

For use on systems with earth current compensation, it is an advantage of connections using two (or one) relays over those with three, that the selective isolation of one of two simultaneous earth faults is easily accomplished. On the other hand, there is no standby relay in case of one failing, except, of course, in the next station. Table VI gives a summary of the most important distance relay connections, with their respective time factors and numbers of relays operating with correct time lag.

As compared with single-relay connections, those with two relays are considerably simpler and the number of transfer contacts is not so great.

(*c*) *Connections using one Relay.*

(1) *Connections with two Current Transformers.* The current path of the relay may be connected in various ways. If two current transformers are connected, as in Fig. 121, the relay coil is supplied with the following currents—

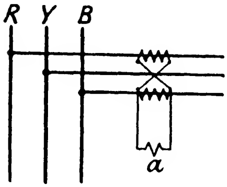


FIG. 121. CURRENT PATH OF ONE DISTANCE RELAY WITH TWO CURRENT TRANSFORMERS

a = Current coil of relay

In the event of a three-phase short-circuit: $(\sqrt{3})\, I$;

In the event of a two-phase short-circuit between the two phases equipped with current transformers: $2I$;

In the event of a two-phase short-circuit between one of the two phases equipped with a current transformer, and the third phase: I.

A single-phase earth in the third phase would not be indicated, so that a connection using only two current transformers cannot be used for protection from single earth faults of a system with solidly earthed neutral.

In order to obtain equal releasing times, i.e. equal values of τ on two-phase and three-phase faults, the above currents must be combined with suitable voltages, to be selected from Table V. One way of achieving this is to put the voltage path on line voltage in the case of a three-phase short-circuit, when the effect of V and $(\sqrt{3})\, I$ is to make $\tau^{\text{III}} = 1$; also on line voltage, under a two-phase short-circuit between the two phases equipped with current transformers, when V and $2I$ give $\tau^{\text{II}}_{RB} = 1$; and on half line voltage in the event of a two-phase short-circuit between one of the phases with, and the one without a current

transformer, so that $\frac{1}{2}V$ and I will again give $\tau^{II}_{RY} = 1$. An appropriate connection is shown in Fig. 122. Alternatively, the current through the relay may be halved, either by shunting or by means of a tapped auxiliary current transformer, in the event of three-phase faults and of two-phase shorts between the two phases equipped with current transformers; when the respective effects of V and $(I\sqrt{3})/2$ will make

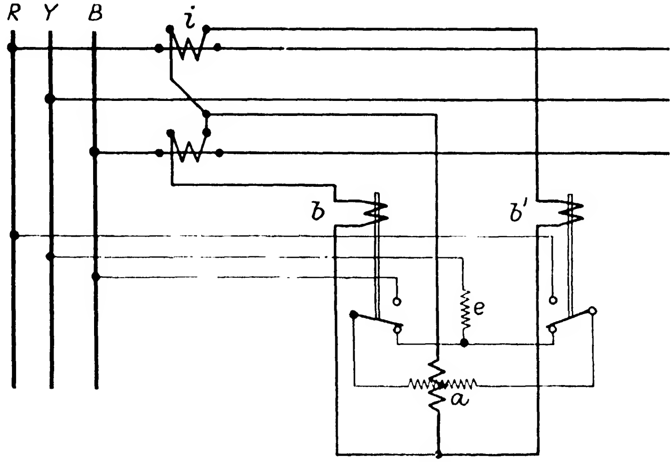


FIG. 122. SINGLE-RELAY CONNECTION GIVING EQUAL TRIPPING TIMES ON TWO-PHASE AND THREE-PHASE FAULTS

a – Distance relay *b, b'* - Starting *i* - Current Transformers

$\tau^{III} = 2$, of V and $2\,I/2$ will make $\tau^{II}_{RB} = 2$, and of V and I will make $\tau^{II}_{RY} = 2$.

Any of the above connections may be modified, so as to give selective discrimination between two simultaneous earth faults, in a similar manner to the one shown above for a connection using two relays. But in this case three current transformers are required, if equal results are to be obtained in all possible cases.

(2) *Connections with three Current Transformers.* If three current transformers are used, the relay can be made to carry either line current (with star-connected current transformers), or the resulting current of two of three delta-connected current transformers, provided transfer contacts are arranged in the current circuits. Without using such transfer contacts, non-symmetrical faults, i.e. single or double earth faults, can be dealt with by a residual current connection, as shown in Fig.

123. The current path of the relay is here connected in the mutual return of the three star-connected current transformers; f is a small compensating impedance of value equal to that of the starting element coils b and b'. Thus, the current path of the relay is energized by earth current in the event of a single or double earth fault, and the resulting value of τ^{I} is about 2. No current would flow through the current path in

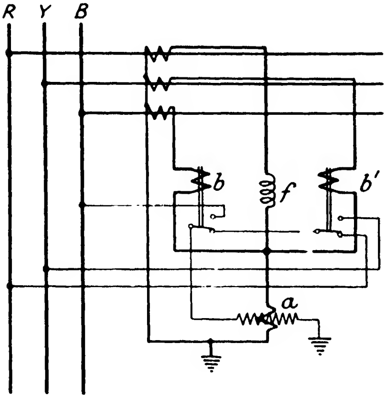


FIG. 123. RESIDUAL CURRENT CONNECTION FOR EARTH FAULTS

a = Directional and time elements
b, b' = Starting elements
f = Compensating impedance

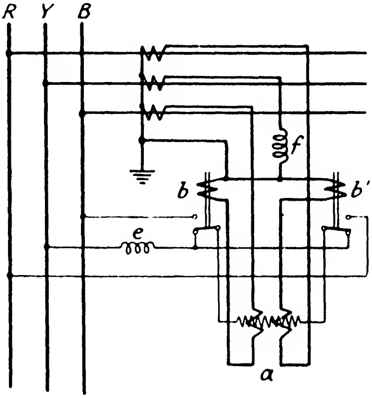


FIG. 124. SINGLE-RELAY CONNECTION FOR SHORT-CIRCUITS

a = Directional and time elements
b, b' = Starting elements
e = Series impedance
f = Compensating impedance

case of phase-to-phase faults, so that this connection is not suitable, except for protection from earth faults.

Protection from two- or three-phase short-circuits can be achieved, if the current path is split into two halves, as shown in Fig. 124. A three-phase short will then cause the relay to be energized by $(\sqrt{3})I$ and V so that $\tau^{III} = 1$. In the case of a two-phase short between R and B, the relay is on $2I$ and V, so that $\tau^{II} = 1$. A two-phase short between either R or B and Y causes one of the two transfer contacts to operate; the relay is energized by I and the voltage between R (or B) and Y. If this voltage is halved by a series impedance e, τ^{II} is again 1.

If a single distance relay is to be used for full protection against both short-circuits and earth faults, a more elaborate scheme of transfer contacts is required. An example of connections suitable for use on a system with earthed neutral

TABLE VI

Principal Distance Relay Connections and Their Main Properties

Connection as in Fig.	Applicable to Following Methods of Earthing the Neutral	Current Path	Voltage Path	τ^{III}	τ^{II}	τ^{I}	τ^{D}	No. of Relays Operating				No. of Transfer Contacts
								Three-phase Short	Two-phase Short	Single-phase Earth	Two-phase Earth	
						(a) Connections Using Three Relays						
109	Any	I	V	$\sqrt{3}$	2	—	—	3	1	—	—	—
110	Any	I	V_{ph}	1	—	—	—	3	—	—	—	3
		I	$\frac{1}{2}V$	—	1	—	—	—	2	—	—	
111	Any	$(\sqrt{3})I$	V	1	—	—	—	3	—	—	—	—
		$2I$	V	—	1	—	—	—	1	—	—	
112	Any	I	V	$\sqrt{3}$	2	—	—	3	1	—	—	3
		I	V_{ph}	—	—	about 2	about 2	—	—	1	2	
113	Any	I	V	$\sqrt{3}$	2	—	—	3	1	—	—	3
		I	V_{ph}	—	—	about 2	about 2	—	—	1	2	
115	Any	I	V_{ph}	1	—	—	—	3	—	—	—	4
		I	$\frac{1}{2}V$	—	1	—	—	—	2	—	—	
		I	$\frac{1}{2}V_{ph}$	—	—	about 1	about 1	—	—	1	2	
116	Any	$(\sqrt{3})I$	V	1	—	—	—	3	—	—	—	3
		$2I$ / I	$\left.\begin{matrix} V \\ \frac{1}{2}V \end{matrix}\right\}$	—	1	—	—	—	3	—	—	
		I	$\frac{1}{2}V_{ph}$	—	—	about 1	about 1	—	—	2	3	
117	Solid earthing	I	V_{ph}	1	—	—	—	3	—	—	—	13
		I	$\frac{1}{2}V$	—	1	—	—	—	2	—	—	
		$I \overset{\wedge}{+} K \times I_E$	V_{ph}	—	—	1	—	—	—	1	—	
		$I \overset{\wedge}{-} \frac{1}{3}I_E$	$\frac{1}{2}V$	—	—	—	1	—	—	—	2	
118	Solid earthing	I	V_{ph}	1	—	—	—	3	—	—	—	4
		I	$\frac{1}{2}V$	—	1	—	—	—	2	—	—	
		$I \overset{\wedge}{+} K \times I_E$	V_{ph}	—	—	1	1	—	—	1	2	
						(b) Connections Using Two Relays						
119	Any	I	V	$\sqrt{3}$	2	—	—	2	1	—	—	2
120	Petersen coil	I	V_{ph}	1	—	—	—	2	—	—	—	5
		I	$\frac{1}{2}V$	—	1	—	—	—	1	—	—	
		I	$\frac{1}{2}V_{ph}$	—	—	—	about 1	—	—	—	1	
						(c) Connections Using One Relay						
122 or 124	Any	$(\sqrt{3})I$	V	1	—	—	—	1	—	—	—	2
		$2I$ / I	$\left.\begin{matrix} V \\ \frac{1}{2}V \end{matrix}\right\}$	—	1	—	—	—	1	—	—	
123	Solid earthing	I	V_{ph}	—	—	about 2	about 2	—	—	1	1	2
125	Solid earthing	See Table VII		$\sqrt{3}$	2	about 2	about 2	1	1	1	1	12
126	Solid earthing	See Table VIII		2	2	about 2	about 2*	1	1	1	1	10
127	Petersen coil	See Table IX		2	2	—	2	1	1	—	1	11

* As may be seen from Table VIII, connections are not symmetrical in the event of double earth faults, i.e. the operating times differ according to the phases affected. In theory, more even results can be obtained if separate adjustable earth windings are added on the auxiliary transformer, and the number of selector contacts is increased to 14. Apart from the undesirable complication, results are still not uniform, since the value of earth current in a system with solidly earthed neutral varies in accordance with the relative location of the faults and earthing point (or points). Therefore, preference is given to the simpler scheme as in Fig. 126 with only 10 selector contacts.

is given in Fig. 125. The current path of the relay is connected to an auxiliary current transformer. Table VII shows which transfer relays operate with various types of faults, and also indicates which of the auxiliary current transformer windings are energized, and by what current. Further, the voltage

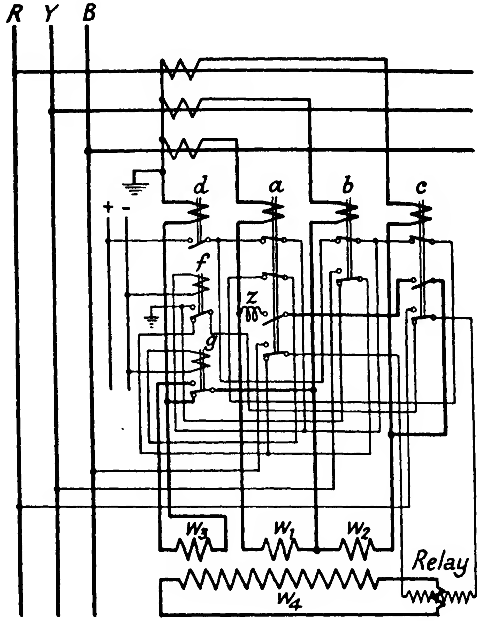


FIG. 125. SINGLE RELAY CONNECTION GIVING FULL PROTECTION OF SYSTEM WITH SOLIDLY EARTHED NEUTRAL

a, b, c = Starting elements
d = Residual current relay
f, g = Auxiliary relays
W_1, W_2, W_3, W_4 = Windings of auxiliary current transformer
z = Shunt impedance ($= W_1 + W_2$)

supplied to the voltage path of the relay and the resulting time factors are indicated.

If the earth impedance differs considerably from that of a conductor, a rough compensation may be achieved by inserting suitable series impedances in the voltage circuits; but even then the method remains imperfect.

Better results are obtained with a connection shown in Fig. 126, which is also suitable for a system with solidly earthed neutral. The respective details are scheduled in Table VIII. Where still more accurate operation is desired in the event of

single and double earth faults, the earth current can be introduced as already explained. In view of the great number of transfer contacts then required it is preferable in such cases to use a connection with three relays.

TABLE VII

OPERATION OF RELAY CONNECTED AS IN FIG. 125

Type of Fault	Transfer Relays Operating	Auxiliary C.T. Windings Energized	Current in Auxiliary C.T. Windings	Relay Voltage	Time Factor
Single-phase earth, *R*	*c, d, f*	W_2	I_R	V_{RE}	about 2
Single-phase earth, *Y*	*b, d, f, g*	W_3	$-I_Y$	V_{EY}	about 2
Single-phase earth, *B*	*a, d, f*	W_1	$-I_B$	V_{EB}	about 2
Two-phase short, *RY*	*b, c*	W_2	I_{RY}	V_{RY}	2
Two-phase short, *RB*	*a, c*	$W_1 + W_2$	$\frac{I_{RB}}{2}$	V_{RB}	2
Two-phase short, *YB*	*a, b*	W_1	I_{YB}	V_{YB}	2
Double earth, *RY*	*b, c, d, f*	W_2	I_R	V_{RY}	about 2
		W_2	$\frac{I_R}{2}$		
Double earth *RB*	*a, c, d, f*	W_1	$-\frac{I_B}{2}$	V_{RB}	about 2
		equivalent:			
		W	$\frac{I_R \hat{-} I_B}{2}$		
Double earth *YB*	*a, b, d*	W_1	$-I_B$	V_{YB}	about 2
		W_1	$I_{YB} \simeq \frac{I_Y}{2} \cdot \sqrt{2}$		
Three-phase short *RYB*	*a, b, c*	W_2	$I_{RY} \simeq \frac{I_Y}{2} \cdot \sqrt{2}$	V_{RB}	$\sqrt{3}$
		equivalent:			
		$W_1 + W_2$	$\frac{I_{RY} \hat{+} I_{YB}}{2} \quad \frac{I}{2}$		

An example of a connection using one single relay for full protection of a system with insulated neutral and Petersen coil, is illustrated in Fig. 127; Table IX shows the results obtained with this connection.

The method employed for selective discrimination between two earth faults is of particular interest. Taking as an example a fault affecting phases *R* and *B*, the voltage and current diagrams at various points of a line are indicated in Fig. 128. The conditions are those prevailing on a typical 33 kV overhead line fed from both ends. From Table IX it will be

seen that each relay is energized by the current I_R and those between the two faults also by a certain portion of the secondary residual current, which is proportional to the primary earth current. The voltage path of all relays between the two faults is on the voltage between *R* and earth, that of relays

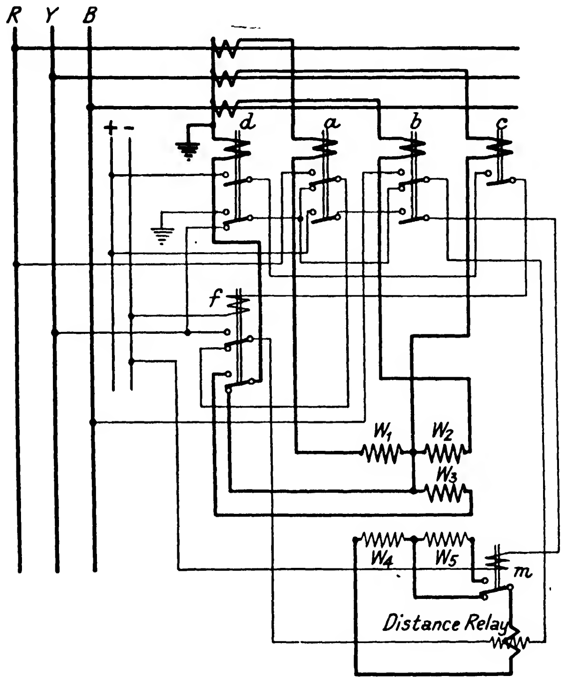


FIG. 126. ANOTHER SINGLE-RELAY CONNECTION GIVING FULL PROTECTION OF SYSTEM WITH SOLIDLY EARTHED NEUTRAL

a, b, c, d = Starting elements
f, m = Auxiliary relays

W_1, W_2, W_3 = Primary winding } of auxiliary current transformer
W_4, W_5 = Secondary ,, } of auxiliary current transformer

outside on line voltage V_{RB}. The resulting primary impedances recorded in each station are given in the drawing. Actually, only one relay (3*b*) trips its circuit-breaker on the high-speed step. A number of others are ready for delayed operation.

As soon as the circuit-breaker 3*b* has opened and the line is divided into two sections, conditions on the line become different. Each half is left with one single earth fault and operation continues, if the two halves are fed from two independent sources, without any further interruption. If, however,

the two ends are linked together over other paths, the system as a whole remains still affected with a double earth fault, and the new distribution of voltage and currents is also indicated in Fig. 128. All relays to the left of station 3 return to

TABLE VIII

OPERATION OF RELAY CONNECTED AS IN FIG. 126

Type of Fault	Transfer Relays Operating	Auxiliary C.T. Windings Energized	Current in Auxiliary C.T. Windings	Relay Voltage	Time Factor
Single-phase earth, R	a, d	W_1	I_R	V_{RE}	about 2
Single-phase earth, Y	c, d, f	W_3	I_Y	V_{YE}	about 2
Single-phase earth, B	b, d	W_2	$-I_B$	V_{EB}	about 2
Two-phase short, RY	a, c	W_1	I_R	V_{RY}	2
Two-phase short, RB	a, b, m	$W_2 + W_1$	$I_R \times \frac{1}{2}$	V_{RB}	2
Two-phase short, YB	b, c	W_2	I_Y	V_{YB}	2
Double earth, RY	a, c, d, f	W_1 W_3 equivalent: W	I_R I_E $I_R \overset{\wedge}{+} I_E$	V_{YE}	> 1*
Double earth, RB	a, b, d, m	W_1 W_2 equivalent: W	I_R $-I_B$ $I_R \overset{\wedge}{-} I_B$ $\times \frac{1}{2}$	V_{RB}	about 2*
Double earth, YB	b, c, d, f	W_2 W_3 equivalent: W	$-I_B$ I_E $-(I_B \overset{\wedge}{-} I_E)$	V_{YB}	about 2*
Three-phase short, RYB	a, b, c, m	W_1 W_2 equivalent: W	I_R $-I_B$ $(\sqrt{3})I$ $\times \frac{1}{2}$	V_{RB}	2

normal immediately, and only relay $4a$ continues to operate, and eventually causes the complete isolation of the fault in phase R. The system continues to operate with phase B on earth. In order to achieve this effect, a voltage relay is added to a connection as in Fig. 127. A voltage relay is also necessary in the case of feeders with open ends, in order to make the system equally selective in case two simultaneous earth faults occur on different feeders.

* See footnote to Table VI.

(*d*) *Interconnection of Distance Relays.*

Distance relays connected in any suitable manner have one disadvantage, viz. that a faulty section is not always disconnected simultaneously at both ends. Where it is necessary to achieve instantaneous isolation from both ends for any

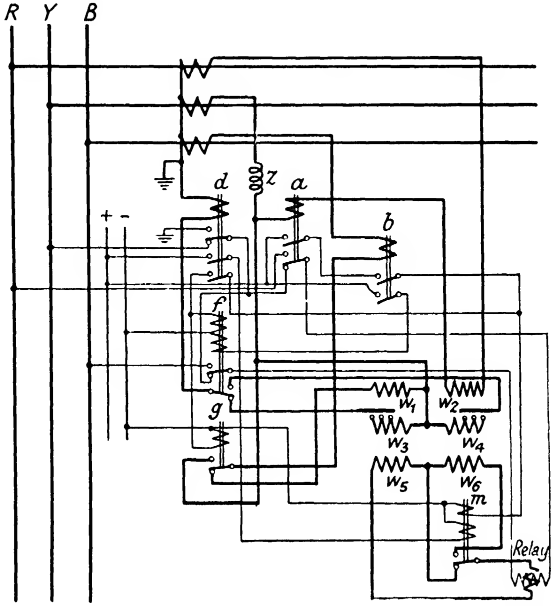


FIG. 127. COMPLETE PROTECTION OF SYSTEM WITH PETERSEN COIL, BY ONE DISTANCE RELAY

a, b = Starting elements
d = Residual current relay
f, g, m = Auxiliary relays

Auxiliary current transformer—
W_1, W_2 = Main primary windings
W_3, W_4 = Adjustable assymmetry windings
W_5, W_6 = Secondary windings
z = Equalizing impedance

position of the fault, the two relays or their tripping circuits may be coupled through a pilot wire or by other means, so that both circuit-breakers are operated by the one relay which measures the lesser distance.* The most complete selectivity is thereby obtained, without any additional gear being required to extend protection to the bus-bars of intermediate stations, or for back-up purposes.

Fig. 129 illustrates the principle of interconnecting two

* See Bibliography Nos. 32, 33.

high-speed distance relays by means of carrier current transmission. The relays are those illustrated in Fig. 106 and need not be explained again. The letters used for the designation of the various contacts correspond to those in Fig. 103.

TABLE IX

OPERATION OF RELAY CONNECTED AS IN FIG. 127

Type of Fault	Transfer Relays Operating	Auxiliary C.T. Windings Energized	Current in Auxiliary C.T. Windings	Relay Voltage	Time Factor
Two-phase short, *RY*	*a*	W_2	I_R	V_{RY}	2
Two-phase short, *RB*	*a, b, f, m*	$W_2 + W_1$ equivalent: W_1	$I_R \times \frac{1}{2}$ I_R	V_{RB}	2
Two-phase short, *YB*	*b, f*	W_1	$-I_Y$	V_{YB}	2
Double earth, *RY*	*a, d, m*	W_2 $K.W_3$ equivalent: W_2	I_R I_E $(I_R \overset{\wedge}{+} K.I_E)$ $\times \frac{1}{2}$	V_{RE}	2
Double earth, *RB*	*a, b, d, g, m*	W_2 $K.W_3$ equivalent: W_2	I_R I_E $(I_R \overset{\wedge}{+} K.I_E)$ $\times \frac{1}{2}$	V_{RE}	2
Double earth, *YB*	*b, d, f, m*	W $K.W_4$ equivalent: W_1	$-I_B$ $-I_E$ $-(I_B \overset{\wedge}{+} K.I_E)$ $\times \frac{1}{2}$	V_{EB}	2
Three-phase short, *RYB*	*a, b, f, m*	W_2 W_1 equivalent: W_2	I_R $-I_B$ $I_R\sqrt{3}$ $\times \frac{1}{2}$	V_{RB}	2

The additional gear comprises on either side a transmitter *S* and a receiver *M*, with coupling condensers *C*. The transmitters are normally in use for remote indication or communication purposes (*F*). In the event of a distance relay operating an auxiliary relay *L* is also energized and its change-over contact *l* switches the transmitter into the circuit, and high frequency current passes continuously along the line as long as contacts t_2 and e_3 remain closed. Contact e_3 belongs to the tripping relay *E*, and interrupts the transmission of high frequency current as soon as one of the tripping relays operates.

On the opposite end contact *l* is also switched over, and the

receiving relay J keeps its contact j open as long as high frequency current continues to be received. A time relay Z is also set in motion and closes its contact z after a short time, just sufficient to prevent tripping before the transmitters were switched over to relay operation. When z has made contact,

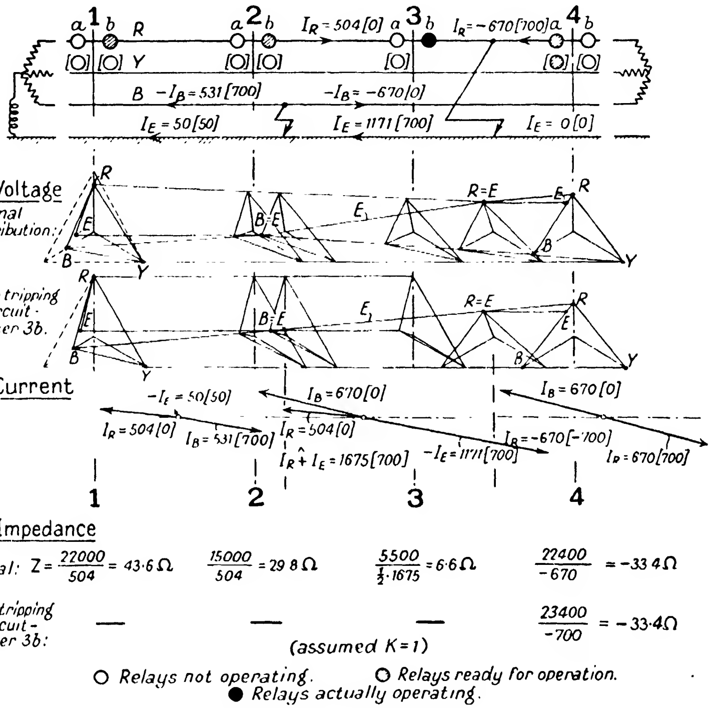


FIG. 128. OPERATION OF IMPEDANCE RELAYS CONNECTED AS IN FIG. 127 (TABLE IX) ON DOUBLE EARTH FAULT

Symbols and figures in brackets refer to conditions after tripping of circuit-breaker 3b.

the circuit on the opposite end is ready for tripping at the instant the high frequency circuit is interrupted, and contact j closed. Thus both relays are forced to operate simultaneously.

In order to achieve high-speed interruption, also in case of the line being fed only from one end, and with a fault near the remote end, the equipment has been supplemented by an under-voltage relay whose contact u energizes an auxiliary relay T. In this case the contact t_2 interrupts the high

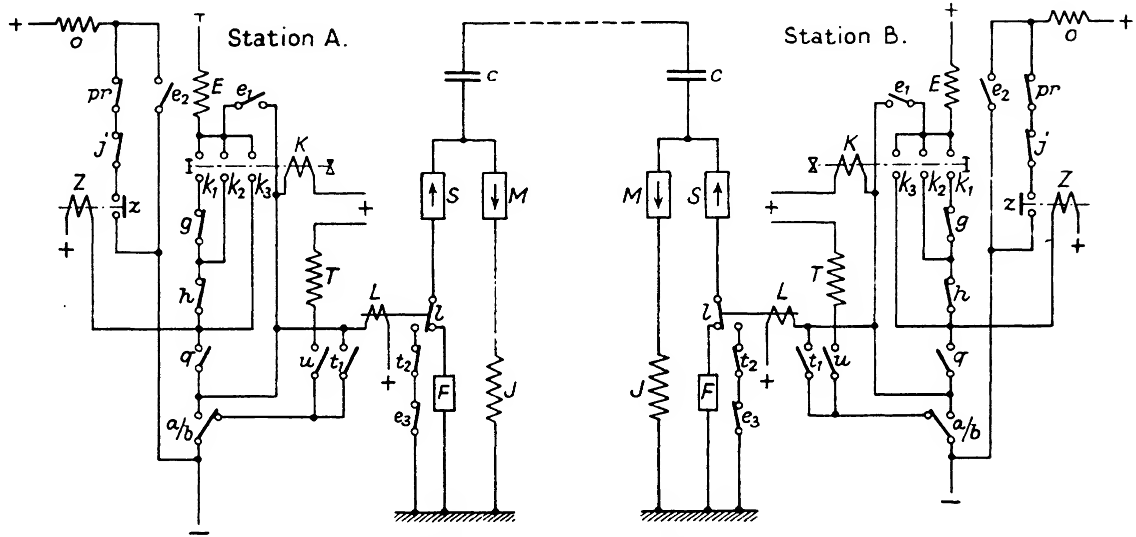


FIG. 129. HIGH-SPEED DISTANCE PROTECTION WITH CARRIER CURRENT TRANSMISSION

$a\ b$ = Alternative contact operated by starting elements A or B
C = Coupling condenser
E = Tripping relay with self-holding contact e_1, tripping contact e_2 and h.f. interrupting contact e_3
F = Telephone or remote measuring equipment
g, h = Contacts of over-impedance relays G and H
J, j = Receiving relay
K = Multistep time element with contacts k_1, k_2 and k_3
L, l = Auxiliary relay
M = Receiver
o = Trip coil of circuit-breaker
pr = Separating contact of an alarm relay
q = Contact of directional element Q
S = Transmitter
T = Auxiliary relay with self-holding contact t_1, and h.f. interrupting contact t_2
u = Contact of an under-voltage relay
Z, z = Short-time relay

frequency circuit. In order to give the alarm in case of any fault in the high frequency equipment, an alarm relay is always installed in connection with the same. A contact *pr* may be added to this relay which makes the two distance relays independent of each other.

Selective Earth Fault Indication. In ring mains or interconnected networks it is necessary to instal relays indicating the location of a fault.

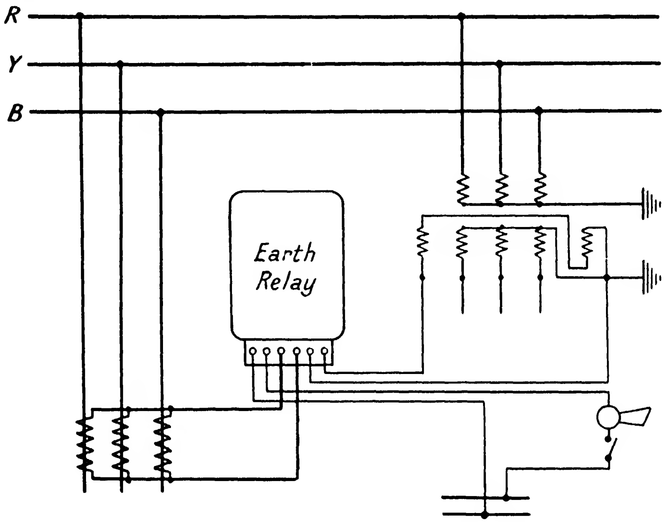


FIG. 130. CONNECTION OF WATTMETER TYPE EARTH RELAY

Any fault dealt with by a distance relay, whether its action leads to eventual tripping of the breaker or not, is automatically notified and its location indicated by the position of a trailer drum on the relay; with high-speed relays a flag indicator shows in which zone the fault is situated, which is at least some indication. There are, however, faults that do not cause any distance relay to operate, notably single earth faults in systems with insulated neutral.

These faults must also be located, in order to take measures for their timely elimination, either by the automatic action of earth relays, or by other means. In a system not protected by a Petersen coil, the capacitive out-of-balance current would be suitable for discrimination. If, however, the earth current is suppressed by a Petersen coil, the position of a fault can only

be indicated by relays influenced by both the neutral voltage and the neutral current, i.e. by "neutral power." Such relays are of the wattmeter type, and must be highly sensitive. Their operation is based on the fact that the voltage between neutral and earth is almost constant throughout the whole system, whereas the leading earth current is highest near the fault, and the lagging (coil) current is of constant value between the Petersen coil (or coils) and the fault. Both these currents have a wattful component due to ohmic resistance and insulator leakage. The two wattful components add together and the resulting wattful current increases gradually towards, and is highest at, the fault. The connections of such an earth indicating relay which, being of the wattmeter type, has of course directional properties, are shown in Fig. 130.

CHAPTER VIII

L.T. NETWORKS

General. In densely populated city areas the consumption of electricity has reached dimensions which supply authorities sometimes find difficult to handle with the existing distribution plant. New cables have frequently to be added, or new substations to be interposed between existing ones. Such gradual alterations, though of little importance individually, tend in their aggregate effect to make the whole system complicated and liable to undesirable incidents. Most existing l.t. networks are found to be the aggregate result of many hundred local extensions and alterations, rather than a well-planned scheme.

In view of the gradual increase of electricity consumption, this state of affairs cannot always be helped. The result, however, is an unnecessarily large number of substations. In order to reduce the cross-sections of cables, and with a view to keeping the voltage drop reasonably low, it is, of course, desirable to have every consumer fed from as many adjoining substations as possible. From this point of view there are three distinct systems of l.t. distribution, viz.—

The *open* network in which each substation feeds into its own section only;

The *partly interconnected* network in which a limited number of sections are interconnected, normally across high power fuses; and

The *fully interconnected* network which consists of a solid grid of l.t. cables over the whole area of a district, with all substations feeding into it.

Fully Interconnected Networks. This last system has the obvious advantage of excluding the possibility of the interruption of supply to any one section (unless the whole of the h.t. supply breaks down), provided the following conditions are suitably fulfilled—

(1) l.t. faults must clear themselves on the spot, so as to affect a minimum number of consumers only;

(2) suitable means must be provided for dealing with the very high reverse currents occurring in the event of a faulty h.t. feeder or transformer;

(3) the scheme must be applicable to existing networks without costly alteration and, if possible, should bring about a reduction of initial and running expenses.

Before dealing with these three fundamental requirements in greater detail, it may be mentioned that the Berlin Electricity Supply Co. (BEWAG), in co-operation with the A.E.G., solved them to their fullest satisfaction, and also found a number of incidental advantages (see below) attaching to interconnected operation. This form of operation of l.t. networks has, in fact, been standard practice in a number of towns in the U.S.A. for many years; all these installations, however, are operated with voltages of only 125/216, and, therefore, American experience and apparatus could not be relied upon when voltages of 220/380 or 230/400 had to be dealt with.

CLEARING OF FAULTS IN THE L.T. NETWORK. Two methods present themselves for consideration, viz.

(a) the use of fuses at junction points;

(b) the "burn-out" method, with the cable itself acting as a fuse.

Which of the two ought to be applied depends on a variety of factors, including the voltage, the type of cable, the depth and method of burying cables, the properties of the soil, network arrangement, etc.

(*a*) *The Fuse System.* In the event of a short-circuit or earth fault in a fully interconnected network, very high currents will flow into the fault; at a comparatively small distance from the fault, however, currents will be only a fraction of the total fault current, due to the multitude of paths available. In order to limit the interruption of service to the faulty cable section, junction point fuses must be able to deal with the maximum short-circuit currents which can possibly occur, and on the other hand, must act with considerable delay at lower currents. Fuses complying with these conditions were not available until a few years ago. As an example, the characteristics of a recent type of junction point fuse are given on p. 159.

With very high currents, the interruption is so rapid as to occur before the peak of the short-circuit current is reached, so that the current actually broken is considerably lower.

To give this result the fusible element must be designed with as small a thermal capacity as possible so that the pre-arcing period on short-circuit is a minimum.

During the arcing period immediately following cutting off, the interaction of the arc with the fuse filling inserts a gradually increasing resistance in the arc path, resulting in a smooth fall of current to zero without any excessive pressure rise in the circuit.

Short-circuit Current	Fusing Time
40 000 A.	0·006 sec.
20 000 „	0·02 „
10 000 „	0·08 „
5 000 „	0·43 „
2 500 „	2 „
1 000 „	42 „

These fuses are of such size and design that they can be installed in existing junction boxes. Fig. 131 illustrates a typical design.

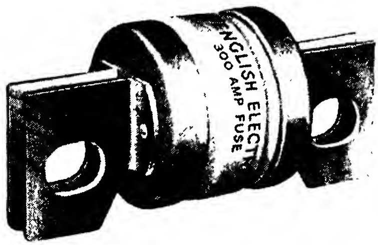


FIG. 131 JUNCTION BOX FUSE
(*English Electric Co.*)

(*b*) *The Burn-out System.* While the blowing of junction-box fuses cuts out a whole cable section, the effects of a fault can be further localized by relying on the cable itself to burn out in the immediate neighbourhood of the fault. With this system of protection, the heaviest short-circuit will interrupt the supply to one or a few houses only, and under favourable conditions to none at all. Of course, many objections have been raised against this crude method, and therefore the Berlin Electricity Supply Co. have carried out extensive model and

service tests.* These tests were made on various types of cable laid in air, in sand with brick covering, in steel tubes and in fibre tubes, and led to valuable conclusions. They have established the fact that all faults to earth, and also phase shorts up to a current of 18 000 A, have invariably been cleared in less than 3 sec. by the cable's burning out. Hence, a number of interconnected network districts in Berlin were fitted with reactors limiting the maximum short-circuit below that value, and have been operating satisfactorily without fuses for a number of years.

Conclusions. In view of the undoubted success of the two alternative systems, it is not possible to state, in a general way, which should be given preference. This decision will have to be made on the special merits of each individual case. At any rate, the protection of a network against l.t. faults may be considered as no longer offering any difficulties, and this achievement has cleared the road towards interconnecting of 230/400 volt networks, with its enormous technical and economic gains.

FAULTS IN H.T. FEEDERS OR WITHIN SUBSTATIONS must be dealt with from two aspects—

(*a*) For the purpose of clearing a faulty feeder on the high tension side, the supply ends of h.t. feeders must be protected by circuit-breakers of sufficient rupturing capacity, operated by suitable excess current, differential, directional or distance relays.

(*b*) A faulty h.t. feeder, with the l.t. system fully interconnected has current fed back into it from the l.t. side across the transformer station (or stations) connected to this feeder. Hence, a protective device against reverse power becomes necessary in every substation. This device takes the shape of a reverse-power relay tripping an l.t. circuit-breaker in the event of current flowing from the network into the substation.

On the other hand there is no need, nor is it desirable, for a substation to be equipped with any excess current protection against forward current, either on the h.t. or the l.t. side. The circuit-breaker must be capable of withstanding the maximum l.t. short-circuit current for several seconds, so as to allow the necessary time for the l.t. fault to clear itself locally, either by means of junction box fuses or the fusing of the cable itself.

* See Bibliography No. 76.

If the substation transformers are to be protected against internal faults between turns which do not cause an excess current or heavy unbalance, Buchholz relays may be installed; in this case a circuit-breaker is required on the h.t. side, or a pair of pilots for tripping the main circuit-breaker of the h.t. feeder. This, however, is often considered unnecessary. The normal practice is to use the Buchholz Relay for giving an alarm, and to omit h.t. switchgear altogether.

The substation thus simplified (see Fig. 132) contains no h.t. switchgear, with, of course, the exception of isolating switches. On the low tension side of the transformer are the reverse power breaker, an ammeter, and the load-sharing reactor.

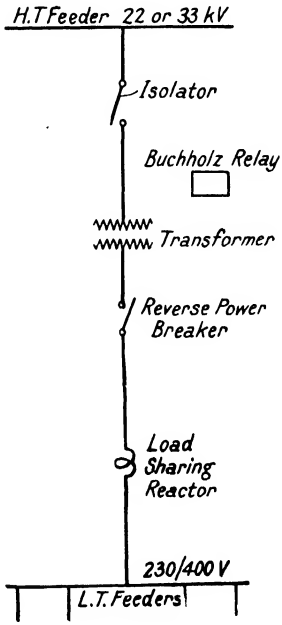


FIG. 132. DISTRIBUTION SUBSTATION FOR INTERCONNECTED NETWORKS

Note the absence of an h.t. circuit-breaker.

ADVANTAGES OF FULLY INTERCONNECTED NETWORKS. It is obvious that in a system on the above lines, an l.t. fault can only bring about an interruption of supply to a small number of consumers close to the faulty point; an h.t. fault only causes the substations on the affected feeder to be separated from the l.t. network, without the l.t. supply being interrupted anywhere. In the event of one or several substations being disconnected, their load is taken over by the neighbouring substations. It is, of course, desirable that substations should share this load evenly, so that no individual one is unduly overloaded. This aim is easily achieved by means of iron packets placed round the leads on the l.t. side.

Provided the reverse current relays are made sufficiently sensitive, the system outlined above also permits the arbitrary disconnection of any number of transformer stations, in order to save their no-load losses in times of light load. Nothing has to be done for this purpose but to open the appropriate feeder circuit-breaker in the power station (or main h.t. switching station); no pilot wires are required. Immediately a

substation is deprived of its h.t. supply, it will take its no-load current from the l.t. network; in other words, reverse power flows across the reverse power relays and trips the breaker.

Whether or not it is desirable to make use of this facility for the purpose of economizing light load transformer losses, depends upon local conditions. It must be borne in mind that the saving will be obtained at the expense of increased copper losses in the l.t. networks, so that in the majority of cases it would be better to give the reverse power relays a less sensitive setting and thereby improve the reliability of the whole system in case of heavy faults.

Reclosing of the reverse-power breaker is of course automatic. It is again achieved without using pilot wires.* Simply by closing the appropriate feeder breaker in the power station, the reverse-power relays are subjected to a differential voltage, and, if the network voltage is below a predetermined value (i.e., if the substation under reference is required), the reverse-power breaker closes.

By interconnecting an l.t. network into one solid grid the voltage becomes practically independent of heavy local current peaks, and even with a plain short-circuit, the drop is only noticeable in its immediate surroundings for about 0·1 sec. This fact permits the use of large squirrel cage motors without special provision for the reduction of starting currents, a great inducement indeed towards more extensive use of electricity!

Another important advantage of low-tension grids is the absence of automatic h.t. switchgear in the substations. This fact makes it possible to dispense with an intermediate voltage, and to connect distribution transformers directly to the 22 or 33 kV supply.

All these advantages are so substantial that, in the author's opinion at least, in point of reliability and economy of operation they render the interconnected system the most satisfactory yet devised, but there are two serious obstacles in the way of its application, viz —

The difficulties involved in converting existing networks to the new system, and

The failure of existing l.t. switchgear to comply with requirements, without exceeding the sometimes very limited space available in the transformer stations.

Regarding the first point, an interesting example is furnished

* Alternatively, where pilots are available, these can take over the function of the reverse-power relays.

by the measures adopted by the Berlin Electricity Supply Co., to extend their network, and to effect a gradual conversion in the most advantageous manner. Where new substations or new cables would formerly have been needed, interconnecting is carried out instead. As a result, interconnected districts gradually increase in size. By such means, at the end of, say

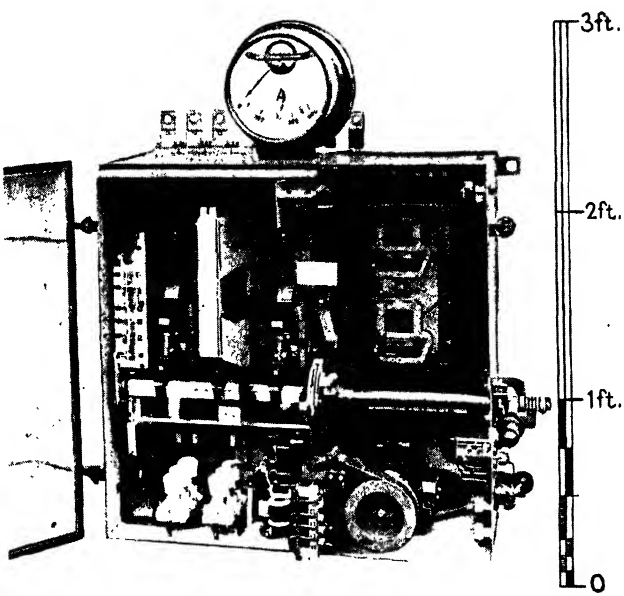


FIG. 133. COMPLETE REVERSE POWER CIRCUIT-BREAKER FOR 230/400 V, 600 A.
(*A.E.G.*)

ten years or more, the whole of a town can be converted without any noticeable increase of expenditure.

Regarding the second difficulty, a great deal of design work has been devoted to the development of a reverse-power breaker complying with the conditions indicated above; the realization of such a breaker was considered impossible a few years ago. Fig. 133 illustrates a 600 A reverse-power breaker of the latest pattern, suitable for short-circuit currents of 30 000 A, and incorporating all relays and additional gear within a space of little over $2\frac{1}{2}$ ft. $\times$ 2 ft. $\times$ $1\frac{1}{2}$ ft.

Economically, interconnected networks, with all their technical advantages, are only applicable to densely populated urban districts.

Earth Faults. The "Station" Switch. It is of great importance that earthed parts of electric appliances for domestic or industrial purposes should not, under any circumstances, acquire a dangerous potential. Under practical operating conditions, it may happen that a fault between a conductor and the earthed neutral causes a dangerous potential on the neutral wire and on all parts earthed through it; at the same time the fault current may be too small to blow a fuse. This is particularly likely where an isolated consumer is fed through a long line of small cross-section, or in old installations where wires of small section are in use. In all such cases the current in the neutral wire may be high enough to cause a bad distortion of the voltage vector diagram, which may lead to the burning-out of lamps.

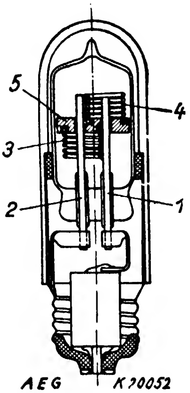


Fig. 134. Cross Section Through a Gas-filled Discharge Tube for 230 V.

(*A.E.G.*)

1, 2 = Carrier rods
3, 4 = Annular-shaped cathodes
5 = Arc-proof insulating barrier

Whereas the current in none of the conductors may be high enough to cause a fuse or circuit-breaker to operate, the neutral current furnishes suitable means of dealing with such faults. A "station" switch—the designation is derived from the fact that, contrary to other means of consumers' protection the apparatus is installed at the substation—is a triple-pole circuit-breaker with a tripping coil connected in the neutral. Of course, the neutral tripping coil may also be fitted to circuit-breakers, having besides, normal overload and short-circuit releases.

The "station" switch will safeguard a system from all single earth faults, except in two cases, which are, earth faults without metallic connection to the earthed neutral, and breakage of the earthed neutral wire itself. Against both these contingencies, the addition of a leakage coil of the Heinisch Riedl type (see Chapter IX) will make the station switch afford complete protection.

Over-voltage Protection. Where low tension lines are carried overhead, surge protection is required just as on h.t. systems.

A gas-filled discharge tube has been found most suitable for this purpose. The operation combines great accuracy with very low time lag. Arresters of this type are connected between each phase wire and earth, and are available for installation indoors or out-of-doors. In outdoor installations the tube may be protected by a metal sleeve.

The principle of operation may be seen from the cross-section shown in Fig. 134. The two sealed-in parallel rods 1 and 2 each

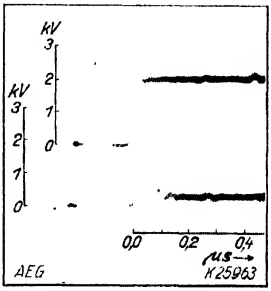


FIG. 135. OSCILLOGRAM SHOWING THE EFFECT OF A GAS-FILLED DISCHARGE TUBE

Top line: Surge on an unprotected 230 V system.
Bottom line: Suppressed surge.

(*A.E.G.*)

carry inside the glass tube an annular-shaped cathode, 3 and 4. The carrier wires are arranged concentrically in respect of the cathodes, and serve as anodes. Thus, there are two discharge arrangements separated from one another by an arc-proof insulating barrier 5. A small damping resistance is connected in series with the discharge tube.

Fig. 135 illustrates the action of a discharge tube. The top oscillogram depicts a surge on an unprotected system. As will be seen from the second oscillograph record, the surge is quenched to about 4 per cent of its original value within a fraction of one-millionth of a second, so that it is rendered entirely harmless.

CHAPTER IX

CONSUMERS' INSTALLATIONS

It is the concern of the supply undertaking to see that an uninterrupted supply of energy is available for the consumers' use, at a voltage neither above nor below a declared value. Further, the supply authority, in order to protect its plant against

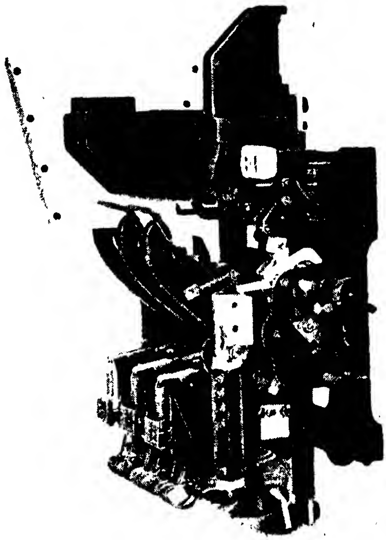


FIG. 136. TYPICAL LOW-TENSION CIRCUIT-BREAKER WITH AIR-BREAK CONTACTS
(Siemens Schuckert Werke)

every possible reaction from faults occurring within the consumers' premises, installs main fuses or an automatic circuit-breaker at the terminals of supply.

The consumer, on the other hand, is interested in the continuous use of current in accordance with his requirements. He, therefore, installs such protective gear as will guard against the operation of the supply undertaking's main fuse or circuit-breaker, to safeguard his own motors, lamps, etc., and to avoid

damage to his premises by fire or otherwise. Hence, all consumers' protective gear is, as a rule, instantaneous acting and, where grading is required, this is preferably achieved by graded current settings.

The use of circuit-breakers is gradually superseding that of fuses. A fuse is mainly a means of protection against short-circuits, and it is less effective in the event of persistent overload. A well-designed circuit-breaker takes care of both types of fault and is, moreover, more economic, inasmuch as it is easily reclosed, without loss of valuable time. For industrial applications, the remote-operated contactor-type breaker is much in use. The air-break (Fig. 136), and oil-break (Fig. 137) types are both equally satisfactory. Ironclad or explosion-proof enclosure may be employed where necessary.

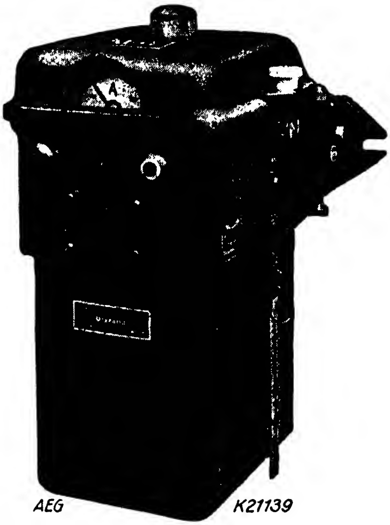


Fig. 137. Oil-immersed Contactor Type Circuit-breaker, 400 V, 60 A.
Rupturing capacity 10 000 A.
Dimensions: 10 × 8 × 12 in.
(*A.E.G.*)

Motor Circuits. Circuit-breakers controlling motor circuits are usually fitted with under-voltage release, in addition to excess-current releases in two or three phases. On correctly designed breakers, separate trip devices are used against short-circuits and overload. These automatic features may, alternatively, be fitted to the starting gear, but it is better practice to mount them on a circuit-breaker of sufficiently high rupturing capacity, and to prevent inadvertent operation by a simple interlock between the breaker and the starter. For cranes and other multi-motor equipments, one circuit-breaker is used for the combined protection of all motors and is fitted with instantaneous-acting short-circuit protection, and in addition with overload releases in each motor circuit.

In large industrial installations the problems of distribution are similar to those in densely populated areas. An interconnected l.t. network protected by reverse power

circuit-breakers offers, in certain cases, a good solution. For particulars see Chapter VIII.

Much of the protective gear actually installed in industrial plant cannot withstand a critical survey. When planning such gear, more attention than is at present usual should be paid to the actual requirements, both regarding short-circuits and overload.

The maximum possible *short-circuit current* for each circuit should be ascertained by calculation, and the magnetic release should be set accordingly. Of course, no great accuracy is required for the purpose of such a calculation. In view of the lowering influence exerted by the arc resistance and by the resistance of contacts, the error will invariably be on the high side. The resulting short-circuit current is determined by the resistance and reactance of the complete circuit from the power station to the fault. The resistance of generators and transformers may be neglected; as to their reactance, if it is not known, it will be sufficiently accurate to assume average values.

All values must, of course, be referred to the voltage of the circuit-breaker, i.e. they must be multiplied by the square of the ratio of transformation. If, for instance, the reactance of an alternator at a voltage of V_A is X_A, the corresponding imaginary reactance X_B in a circuit of V_B volts is

$$X_B = (V_B/V_A)^2 \times X_A \quad . \quad . \quad . \quad (26)$$

The method of calculation may be demonstrated by a short example. A three-phase short-circuit be assumed to have occurred in a 400 V feeder of the system illustrated in Fig. 138 from which the conditions assumed and the process of calculation will be clear.

The resulting fault current is the r.m.s. value of the momentary short-circuit current, not considering the d.c. component. Since consumers' installations are as a rule connected to the power station through lines and transformers of high reactance, the continuous short-circuit current is, as a rule, not much lower than the first half-cycle.

By the short-circuit current flowing in case of a fault immediately behind a circuit-breaker, the required rupturing capacity and the setting of the instantaneous magnetic release are determined.

On the other hand, the *maximum permissible current* for

motors and cables determines the setting of the thermal overload release or overload relays, and also the characteristics of inverse time lag, should this be used. This characteristic must be adapted to existing conditions, and not be selected

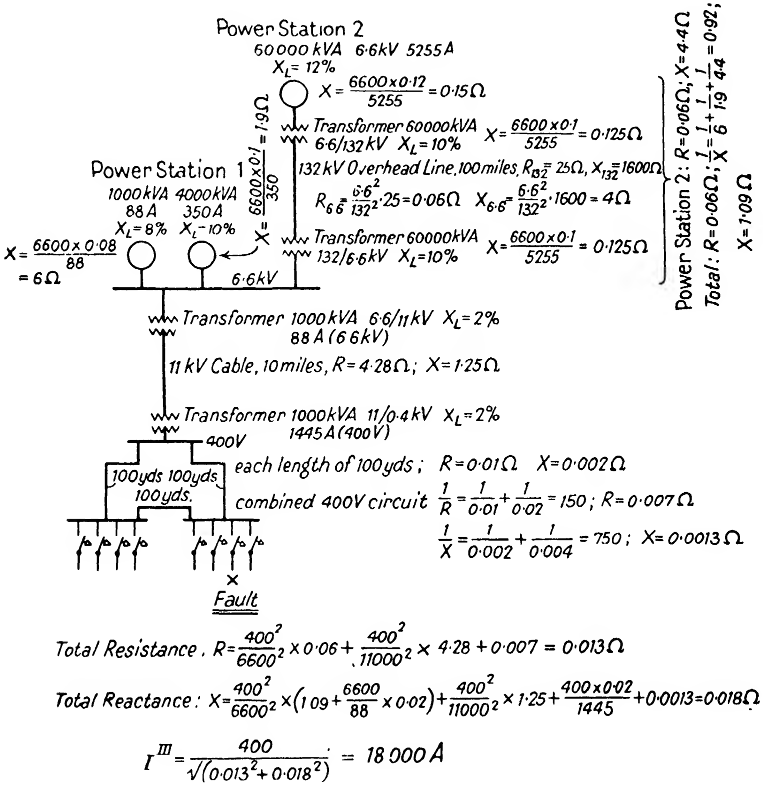


FIG. 138. TYPICAL EXAMPLE OF SHORT-CIRCUIT CURRENT CALCULATION

because it happens to be the manufacturer's standard. The very object of overload protection would be defeated, were the current-time setting more than just a few per cent higher than the permissible maximum. If this is not appreciated, and an arbitrary high setting is used, it will be better to install fuses or circuit-breakers with magnetic release only, thereby saving the extra expense.

Lighting Circuits. Fuses. In lighting circuits the aim of

protection is not so much the protection of lamps as the safety of the whole building or vessel from fire, due to excessive heating of an overloaded conductor.

The protective value of fuses, and more particularly of bare fuse wires, is to a certain extent problematic, since there is nothing but a regulation to prevent users from increasing the size of fuse wires, should they find frequent blowing of fuses inconvenient. With cartridge-type fuses it is made more difficult to increase the fuse rating arbitrarily, since it is necessary to exchange the fitting (gauge ring or contact screw) as well in order to insert a cartridge of higher rating.

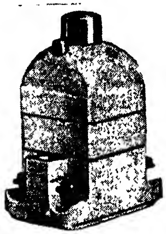


FIG. 139. TYPICAL MINIATURE CIRCUIT-BREAKER
(*Stotz A.G.*)

The difficulty of correct protection for domestic lighting and general circuits is accentuated by the fact that it has been, and in spite of the new revised regulations will to a great extent remain, common practice not to install separate fuses for each sub-circuit. Hence the danger of overloading one sub-circuit without blowing a fuse is always imminent.

Miniature Circuit-Breakers. The application of miniature circuit-breakers with overload and short-circuit releases cannot be recommended with too much emphasis; in fact, their use has been made compulsory in several districts abroad. In Germany alone, about five millions of miniature circuit-breakers are actually installed. There are, however, not many designs whose rupturing capacity and other properties are adequate.

These circuit-breakers are encased in a sealed porcelain body and are not adjustable. Hence the consumer is prevented from increasing the overload and short-circuit settings. A typical model is illustrated in Fig. 139, while Figs. 140 and 141 explain the mechanical operation. The central push button *l* when pushed in, closes the circuit. The release may be effected by pressing the small push button *k* on models provided with this extra push button, or by overloading or short-circuiting. The flow of the current is indicated in Fig. 141 along the broken line. The operation is as follows:—The current flows through the coil *a*, passing through contact *h* and *g* to the bi-metal strip *o*. On small sustained overloads the bi-metal strip heats up, bends, and at a certain point releases its hold on

the lever *n*, which, in turn, causes the lever fitted immediately above it to rise and release its hold at the elbow connecting the arms *e* and *m*. In this manner the catch is released and, accordingly, opens the circuit between the contacts *h* and *g*. Similarly, on heavy overloads and short-circuits, the solenoid operates the switch. In this case, however, the centre core *c* is attracted upwards by the fixed core *b*, and thereby pushes the centre rod *d* upwards against the release arm, repeating the operation described previously. The connecting arm *m*, is not fixed to the contact arm *e*, but engages in a groove provided for it. In this manner, the release action can take place without the operating push button *l* rising. The switch cannot, therefore, be held in against a short-circuit or overload, and is thus proof against outside interference which might cause damage.

The whole mechanism is fitted in its own framework independent of the porcelain, so that the working remains unaffected if the external casing were damaged.

According to whether the breaker is used for the protection of lighting or power circuits, a different ratio between overload and short-circuit setting, and a different overload characteristic are applied; thus the breakers are made suitable for any class of work, for current ratings up to 25 A at 400 V. In Fig. 142 the tripping characteristic of a wiring-type circuit-breaker is compared with the fusing characteristics of an equivalent fuse and of the corresponding size of rubber-insulated cable. According to British Standard Specification No. 88, a 5 A fuse must sustain a current of 8 A during 30 min., but must be blown

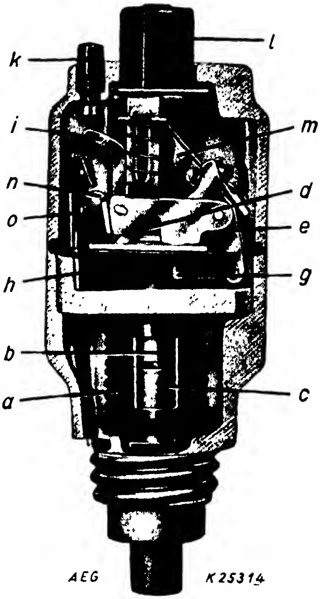


FIG. 140. CROSS-SECTION THROUGH MINIATURE CIRCUIT-BREAKER

a = Magnetic trip coil
b = Fixed core
c = Movable core
d = Connecting rod
e = Contact arm
g, *h* = Contact
k, *i* = Tripping push button
l = Closing push button
m = Connecting arm
n = Releasing lever
o = Bi-metal strip

(*A.E.G.*)

by a current of 9·5 A after not more than 30 min. This specification takes into account the necessarily erratic nature of fuse wire operation. The factor of safety for various overloads

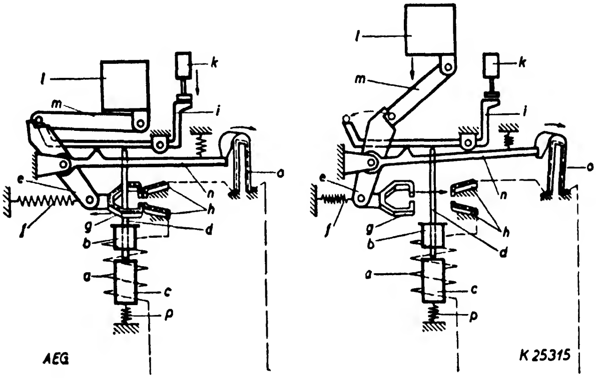


FIG. 141. OPERATION OF MINIATURE CIRCUIT-BREAKER
Left: closed Right: open position

a = Magnetic trip coil
b = Fixed core
c = Movable core
d = Connecting rod
e = Contact arm
f = Spring
g, h = Contact
k, i = Tripping push button
l = Closing push button
m = Connecting arm
n = Releasing lever
o = Bi-metal strip
p = Spring

(*A.E.G.*)

is given in Table X. It will be seen that the factor of safety is not too good under continuous overload, but is unnecessarily high in the case of short-time overloads. The latter feature

TABLE X

EXCESS CURRENT PERFORMANCE OF FUSES AND CIRCUIT-BREAKERS

Duration of Overload	1/0·044 in. V.I.R. Cable	5A Fuse		6A Elfa Circuit-breaker	
Min.	I_{max}	I_{max}	Factor of Safety	I_{max}	Factor of Safety
1	39	9·7	3·77	11·8	3·30
2	30	9·6	3·13	11·0	2·72
5	21	9·5	2·21	10·5	2·00
10	18	9·5	1·90	10·0	1·80
30	15	9·5	1·58	8·0	1·87
over 60	14·5	9·5	1·53	7·5	1·93

causes the frequent blowing of fuses without necessity. In the same table, the corresponding figures of a miniature circuit-breaker with thermal overload and magnetic short-circuit protection, for a nominal current rating of 6 A are given for comparison. Though 20 per cent more load is permitted on the same cable (and still more might in fact be allowed) the safety factor under continuous overload is actually even higher; for

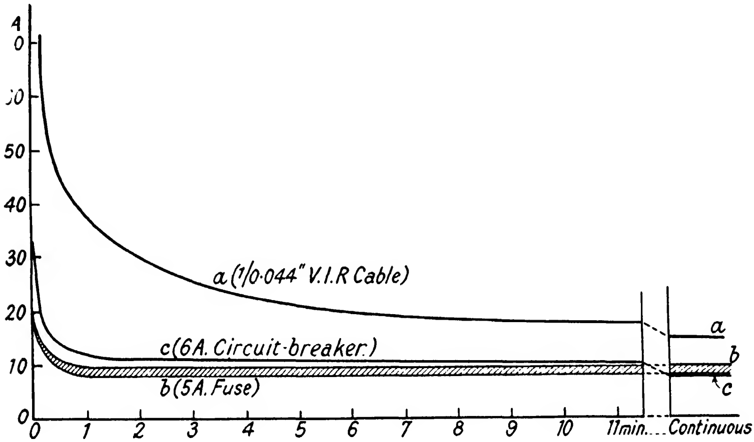


FIG. 142. FUSING OR TRIPPING CHARACTERISTICS OF CABLE, MINIATURE CIRCUIT-BREAKER AND FUSE

heavy temporary overloads, the factor of safety is more reasonable than that of a fuse. In addition the settings of circuit-breakers are, of course, much more accurate, so that higher load currents may be permitted. At the same time real safety is obtained if, instead of fuses, correctly designed circuit-breakers are used. Auxiliary contacts may be fitted for special purposes. Any number of breakers may, of course, be combined in distribution boxes (Fig. 143). In view of the exceedingly small overall dimensions (2 in. dia. × $4\frac{1}{2}$ in. high, for the screw type), the rupturing capacity is amazingly high. The types referred to have been found to stand many hundreds of short-circuits, with currents up to 1 500 A.

Earth Leakage Protection. A great number of fatal accidents have occurred to persons touching earthed parts of electrical apparatus. It is often assumed that the installation of an earthing device is a satisfactory safeguard against earthed

parts assuming a dangerous potential to earth. However, the earth resistance varies with the condition of the soil, and the safety achieved is often imaginary rather than real. Under favourable circumstances the voltage which may involve danger, may be as low as 65 V with human beings and about 24 V with domestic animals.

The practice of connecting all earthed parts to an earthed neutral wire is satisfactory if carried out with the necessary

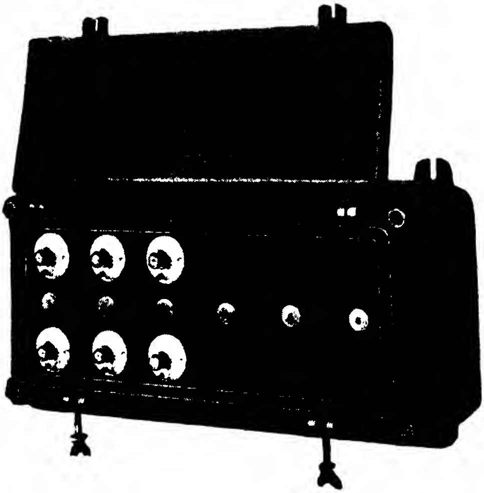


FIG. 143. IRONCLAD DISTRIBUTION BOX WITH MINIATURE CIRCUIT-BREAKERS
(*Wm. White & Co.*)

care (see also Chapter VIII). Even then, however dangerous voltages can arise where the combined resistance of the earth circuit is too high, and consequently the fault current too low to operate the fuse or the excess current release of the circuit-breaker.

Very reliable protection may be achieved by means of the Heinisch-Riedl earth leakage coil, a simple device which can be fitted to any type of l.t. circuit-breaker or switch.

The principle of the Heinisch-Riedl system is illustrated by Fig. 144. The protected parts are connected to a terminal *K*. Another terminal *H* is earthed. Between *K* and *H* a leakage coil is connected which trips the switch when the voltage exceeds 65 (or 24) V. Full safety is still obtained with

an earth resistance as high as several hundred ohms. A testing knob enables it to be ascertained at any time whether the device is operating properly. All switches and circuit-breakers controlling motors, cookers, stoves, or any other appliances with metal casings, should be fitted with a leakage coil. An illustration of a 25 A Heinisch-Riedl switch is given in Fig. 145.

That the value of this device is fully appreciated is shown by the fact that the latest (1934) edition of the *I.E E. Regulations for the Electrical Equipment of Buildings* specifies its use in all cases where the earth resistance exceeds one ohm.

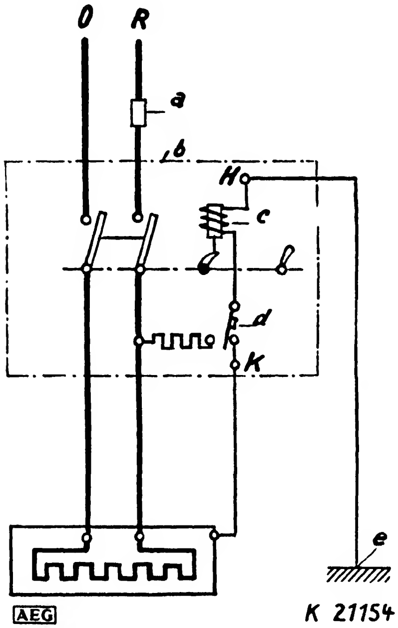


Fig. 144. Connections of Earth Leakage Switch

a — Circuit fuse
b = Protected metal casing
c = Leakage trip-coil
d = Test knob
e — Earth
H, *K* = Terminals
O — Neutral wire
R — Phase wire

Fig. 145. Earth Leakage Switch, 25 A Size

(*A.E.G.*)

Protection of Electronic Valves. Valves are particularly sensitive to excess voltages. Their protection by efficient surge arresters is, therefore, advisable. Discharge tubes such as are described in Chapter VIII (see Figs. 134 and 135) offer full safety, and may with advantage be installed in connection with any sort of control gear, or other apparatus (including wireless sets) comprising electronic valves.

CHAPTER X

THE PROTECTION OF D.C. CIRCUITS

D.C. Circuit-Breakers. The interruption of a direct current arc is much more difficult than interrupting an alternating current arc. In the latter case, the current passes through zero at the

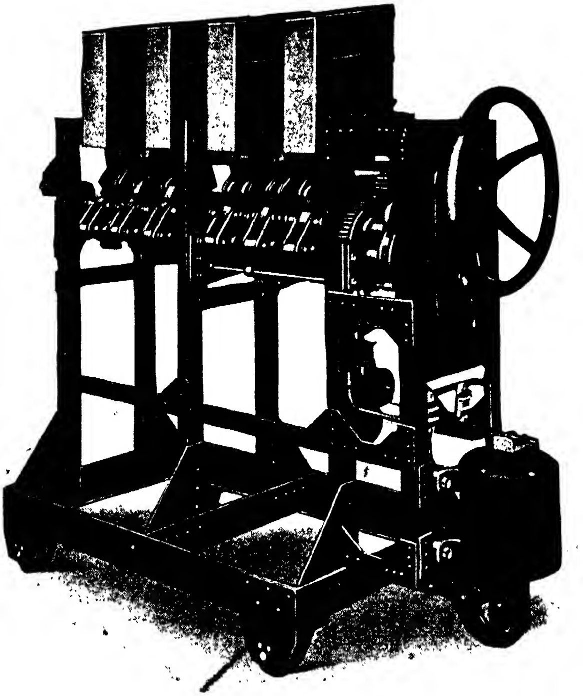


FIG. 146. HIGH-CURRENT D.C. CIRCUIT-BREAKER (*A.E.G.*)

end of each half cycle, and all that has to be done is to prevent restriking.* With d.c., however, the arc must actually be broken. Therefore, d.c. switchgear is designed with a view to high speed separation of the contacts and means are provided

* See Chapter II, p. 20.

for blowing out the arc. The action of a strong magnetic field is most suitable for this purpose.

The high currents often met with in d.c. installations call for special designs of main and auxiliary contacts. A large d.c. circuit-breaker is illustrated in Fig. 146.

High Speed Circuit-Breakers. Modern d.c. circuit-breakers of the high speed type are mainly used for the protection of

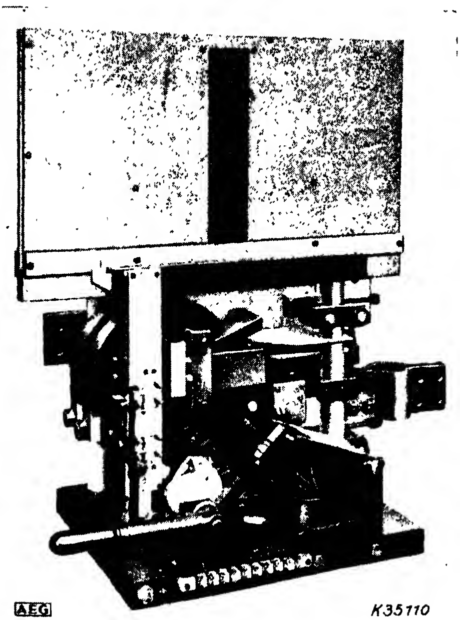


FIG. 147. "GEARAPID" TYPE HIGH-SPEED CIRCUIT-BREAKER
3000 V, 1000 A
(*A.E.G.*)

converters or rectifiers, and interrupt the current within about $\frac{5}{1000}$ sec. This delay is so short that the current, due to the reactance of the circuit, does not have time to rise to more than a fraction of the ultimate short-circuit current.

A typical recent design is illustrated in Figs. 147 and 148. In order to achieve high contact speed from the first instant of motion, the armature (2) is not directly connected to the movable contact arm, but transmits its energy to the contact by impact. Thus, in contrast to older types, the contact speed

is highest in the beginning and decreases before the contact comes to rest, thereby avoiding wear due to sudden stopping. Breakers of this type can be built with or without directional features, for automatic or hand operation, and for all voltages and currents practically occurring in d.c. installations.

Protection of D.C. Generators and Converters. In view of the fact that d.c. generating plant is, as a rule, of moderate capacity, the requirements in respect of rupturing capacity and relay operation are far less stringent than those for a.c. protection.

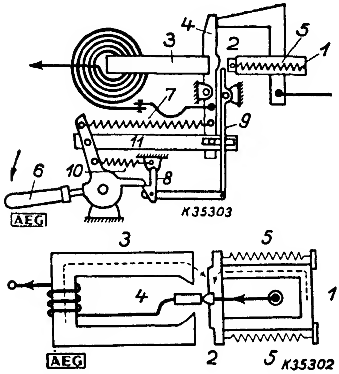


FIG. 148. PRINCIPLE OF "GEARAPID" TYPE HIGH-SPEED CIRCUIT-BREAKER

1 = Holding magnet
2 = Moving armature
3 = Tripping magnet
4 = Movable contact
5 = Springs holding the armature
6 = Handle
7 = Contact spring
8 = Pawl
9 = Tripping Lever
10 = Tripping spring
11 = Locking rod

(*A.E.G.*)

Generators or converters are protected by excess current and reverse power releases. The latter is of particular importance in the case of compound-wound machines, where the reverse current in the series winding causes a dangerous speed rise. Compound-wound machines, even those of small size, must not, therefore, be protected by fuses.

Fuses are also unsuitable in connection with three-wire machines where the interruption must take place simultaneously in both outers.

In the case of large d.c. generators and converters, excess current protection is usually combined with a field-weakening device. On the a.c. side of converters, no-volt release is an essential feature.

Protection of Rectifiers. Considerable excess voltages can occur in rectifier plant in the event of high overload when the rectifiers are cold. Suitable excess voltage arresters must, therefore, be connected between the transformer terminals and earth. No further protective gear is needed except the main h.t. circuit-breaker protecting the transformer to which the rectifiers are connected. The secondary star point is brought out and acts as the negative pole of the d.c. system. In the case of

steel tank rectifiers, this negative pole is led through a high-speed breaker with forward and reverse current releases. The usual procedure is to provide instantaneous action on reverse current, and a time delay on forward excess current. In order to prevent a defective rectifier being connected to the d.c. bus-bars, the sequence of switching operations is regulated by interlocks in such a way that no high-speed breaker can be closed unless the h.t. circuit-breaker has been closed first. A selective relay is also provided for each rectifier, which causes the tripping of both breakers in the event of a reverse current, but trips the high-speed breaker only, when a fault occurs in the d.c. system. Contact type vacuum gauges make it impossible to reclose the breakers unless the vacuum in the tank is adequate. Contact thermometers are installed for automatic interruption in case of excessive heating of a rectifier.

Glass-bulb rectifiers are practically immune from back-firing and require no reverse current circuit-breakers. It is considered sufficient to install quick-acting fuses in each of the anode leads. Provision has to be made against failures of the cooling fan. This is achieved by means of an air baffle, or a no-current relay.

If rectifiers are fitted with grid control, excessive fault currents can be interrupted in a most convenient and simple manner by applying such a potential to the grids that the maintenance of an arc is made impossible. This may be achieved by means of a current transformer in the d.c. mains, and a high-speed relay connected to its secondary winding. In this secondary winding, direct current is generated as long as the current through the primary winding is rising. Thus, a grid-controlled rectifier can be made to act as its own circuit-breaker.

D.C. Feeder Protection. On traction feeders, single pole high-speed circuit-breakers operating on forward current only, are used. In order to avoid reclosing (automatic or by hand) on a dead short, a test contactor and resistance are installed in parallel with each high-speed breaker, so connected that they are inserted before the main circuit-breaker is closed.

Protection of Accumulators. Lead batteries and other types of electric accumulators require protection both in the charging and discharging circuits.

In the discharging circuit, excess current circuit-breakers or fuses suffice; the latter, however, must not be used in three-wire

systems, as the blowing of one fuse would leave one of the two circuits energized.

In the charging circuit reverse current protection must be provided, except when charging by means of a glass bulb rectifier. It is further recommended to install an automatic device to prevent excessive charging. Though the correct state of charge is indicated by the terminal voltage, contact voltmeters are not suitable, as the voltage rise during the final

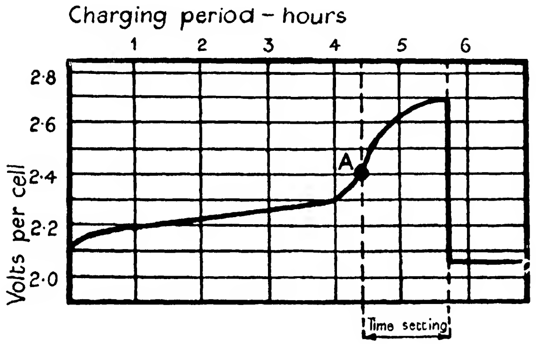


FIG. 149. CHARGING CURVE OF LEAD-ACID ACCUMULATOR CELL

Point *A* is a definite instant which may be used for energizing the time element of a Poehler switch.

phase of the charge is very slow (see Fig. 149), and the inaccuracy of these instruments may allow the charge to be continued for hours in excess of the permissible time. A very successful method of avoiding this deficiency of the contact voltmeter is applied in the Poehler charging switch. This device consists of a contact voltmeter making contact, not when the full voltage is reached, but considerably earlier, at a voltage of about 2·4 V per cell (point *A* in Fig. 149), and a time element which is set according to the battery characteristic, so as to interrupt the charging circuit when the charge is completed. The correct time lag varies with the type and capacity of cells. The arrangement of the combined device is illustrated in Fig. 150. The result of its application is a considerable increase of the life of accumulator plates.

Earth Leakage. Where the midwire or one pole of a system is earthed, an earth fault is equivalent to a single-pole short circuit, and is dealt with by the excess current relays or fuses.

If both poles are insulated, an earth relay is connected as

shown in Fig. 151. An artificial midpoint is obtained by means of a symmetrical auxiliary resistance, and the relay is connected between this midpoint and earth.

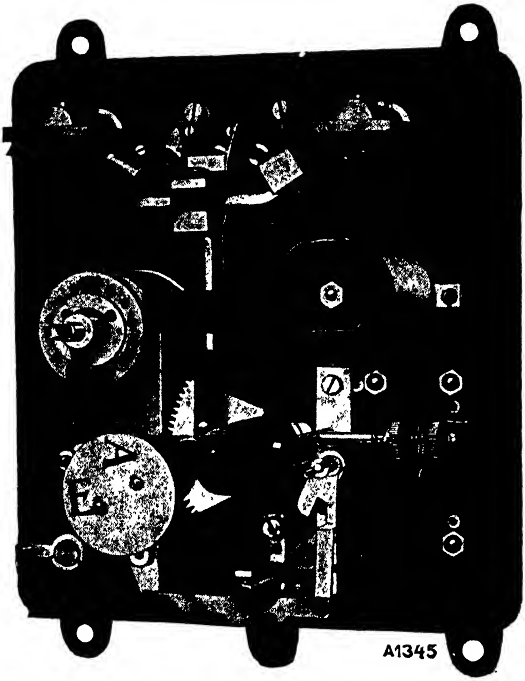


FIG. 150. POEHLER TYPE BATTERY CHARGING SWITCH

Excess Voltage Protection. Where direct current feeders are carried overhead, the machines and other gear connected to

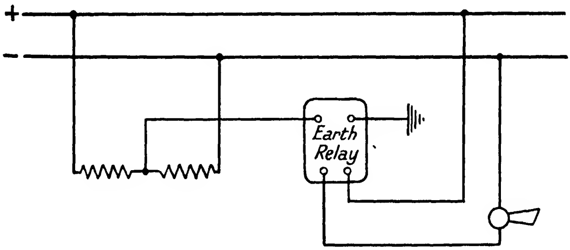


FIG. 151. CONNECTION OF EARTH-LEAKAGE RELAY IN A D.C. TWO-WIRE PLANT

them require protection against over-voltage. Here, the cell arrester is holding its own. It consists of aluminium electrodes, immersed in a suitable electrolytic liquid. The formation of an oxide film round the electrodes makes the normal resistance very high. When a voltage considerably in excess of the rated

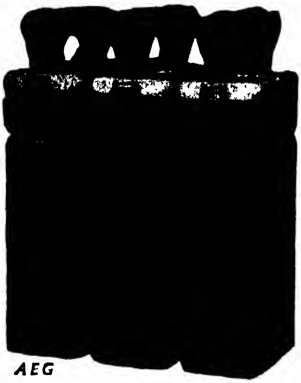


FIG. 152. ALUMINIUM CELL TYPE EXCESS-VOLTAGE ARRESTER FOR DIRECT CURRENT
(*A.E.G.*)

voltage is applied, the film is punctured and the charge is conducted to earth through practically no resistance. The action is instantaneous, and equally satisfactory under static charges or travelling surges. The film is automatically re-formed without delay, so that this type of arrester is most suitable for use on d.c. systems of any voltage. Fig. 152 shows an example of a 750 V arrester which is in extensive use both in stationary plant and on rolling stock. The attendance is limited to a yearly renewal of the liquid.

CHAPTER XI

THE CO-ORDINATION OF PROTECTIVE GEAR

General Considerations. Where means of *preventing* a certain class of fault are available, they should be adopted in preference to means of *protection*. When making a selection between various alternative protective schemes, it must be remembered that the one without, or with the least number of moving parts, is the most reliable. Direct-acting protective devices (see Table III) are, as a rule, the simplest and, therefore, most trustworthy ones, and wherever adequate protection can be achieved by their installation there is no object in resorting to more elaborate schemes.

Thus, it is sound practice to install Petersen coils for protection against earth faults, and excess voltage arresters against damage through excess voltage; to apply h.t. fuses instead of automatic circuit-breakers on spur lines in rural districts; and to rely on the Buchholz relay as the main element for transformer protection. Only generating stations and extensive networks need protection by more elaborate methods.

Earthing of the Neutral. The layout of a protective system, in fact the whole trend in planning, is essentially influenced by the fundamental decision as to whether the neutral of a system is to be solidly earthed or insulated. This question has been dealt with in Chapter VI, but in view of its supreme importance it will be touched upon once more, from a broader point of view.

It is possible, nowadays, to achieve perfect safety of plant with either the earthed or insulated neutral. It must be remembered that this was not the case at one time, over ten years ago, when extensive networks were already in existence in many parts of the world; the widespread prejudice which can still be found against the insulated neutral dates from the time before Professor Petersen invented the earth-suppression coil.

The fear of insulating the neutral was then fully justified, and may have been responsible for the development of such an ingenious design as the non-resonating transformer. The freedom of an "earthed" system from increased voltage in the event of an earth fault is dearly paid for, since the heavy

fault current represents a single-phase short-circuit, and thus means an interruption of service every time. This is very serious in view of the fact that the great majority (in medium voltage systems as many as 90 per cent) of all faults are, or start as, earth faults. The fact that earth faults are usually disconnected instantaneously in systems with solidly earthed neutral, adds to the inconvenience, and introduces much unnecessary confusion into such networks.

Since, in the Petersen coil, a means is now available for suppressing the fault current, the number of interruptions directly due to single-phase earth faults can be greatly reduced. With such a coil in circuit, the majority of these faults are of such short duration that the rise of potential on the two healthy phases is hardly noticeable. Should even a small number of earth faults develop into double earth faults thereby causing interruption, the total number of interruptions will still be much lower than would be the case if no Petersen coil was installed. Only the rare instances of solid earth contact, e.g. by a broken conductor, will cause a persistent rise of voltage to earth by 73 per cent. This is still well under the flash-over voltage, and experience shows that the development of a second earth fault is extremely rare even in foggy weather, or where the insulation is weakened through deposits on insulators of salt or dust. The claim that the Petersen coil actually reduces the number of line interruptions to less than one eighth, is supported by the experience of many years in over a thousand networks.

It is a coincidence that almost the same percentage of interruptions can be rendered harmless with the aid of the very latest improvement* on systems with solidly earthed neutral. But, as compared with the simple and technically perfect solution due to Professor W. Petersen, what a multitude of elaborate apparatus had to be called into play in order to achieve, laboriously and at high cost, the effacement of interruptions instead of their actual elimination!

Incidentally, the Petersen coil has also another beneficial effect, i.e. that of reducing interference to telephone lines.

* See p. 16. It is, of course, not implied that the applications of automatic reclosers were limited to systems with earthed neutral. Since, however, they constitute the only means of reducing the number of line interruptions in such a system, it is obvious that their importance is greatest for lines with earthed neutral. Where a Petersen coil is installed, reclosers are useful to reduce the duration of those few interruptions which are not eliminated by the action of the coil.

In face of such convincing evidence there can be no doubt that, under present conditions, the small saving due to cheaper transformers with graded insulation, cannot justify the admission of eight times as many interruptions of power supply. It is therefore likely that solid earthing will not be employed for new transmission systems. A growing number of networks in this country and elsewhere are being converted from solid to Petersen coil earthing. This fact appears to confirm the author's view that the old controversial question as to the best method of earthing the neutral has been decided in favour of the insulated neutral in connection with the Petersen coil.

If, once and for all this view is accepted, the task of selecting suitable protective gear is made considerably easier. There is no longer any need to differentiate between faults requiring immediate isolation and those which require delayed action. The distance of a fault from the protected point becomes the only determining factor for the protection of distribution networks against those few faults which are not dealt with by the Petersen coils. Hence, the distance relay is now predominant in all extensive installations; this system fulfils all requirements, in particular if high speed relays of proper design are used. Only where, on the score of expense, distance relays cannot be installed, may excess current relays or fuses be used. If a feeder protected by excess current relays is connected to a network equipped with distance relays, it is, of course, necessary for the excess current relays to have such characteristics as will ensure co-operation with the distance relays installed in the main network. The modern tendency is to use multiple definite time lags for both types of relays. With the addition of excess voltage arresters installed in convenient positions, an almost absolute reliability is achieved.

Overall Reliability. Various ways have been indicated in the appropriate chapters for the protection of machinery, apparatus, and transmission lines. It has been shown that, under modern operating conditions, the continuity of supply is a requirement at least as important as the safeguarding of the plant itself.

When deciding upon means of protection, sight is often lost of the basic aim of all protective gear. This aim, primarily, is *not* the maintenance of supply through every link of the supply system itself, but the continuity of supply to consumers

whose equipment or installation is not itself faulty. Hence, every protective scheme must also be closely examined from the viewpoint of overall (as distinct from individual) operating reliability.

Of two or more systems which satisfy equally the two requirements of reliability and stability, the one which offers the greater simplicity and uniformity of equipment, and is, accordingly, easier to operate, test and maintain, will be preferable. Economic considerations should not be allowed to influence a comparison, so long as the cost of protective gear remains within a reasonable proportion of the value of protected plant.

At first glance it would appear that greatest overall reliability is obtained by making each individual section of a plant as proof from damage as is technically possible, within the limits drawn by economic considerations.

By trying to eliminate any and every sort of accident and to build all parts of a scheme with a uniform high factor of safety, the position and nature of a disturbance are entirely left to chance. Hence, it is almost impossible to provide means of protection in all parts of an installation, which may be considered perfect from an up-to-date point of view, without increasing the cost beyond a reasonable figure. Also, from the operating viewpoint it is as undesirable to have too much protective equipment as it is to have too little. An attempt should be made to keep down the quantity of protective apparatus and also to standardize types. Further, it is essential to give preference to devices eliminating or suppressing the source of trouble over those merely averting or reducing consequential damage.

An example may illustrate the essential difference between the modern requirement of uninterrupted current supply to the consumer, against protection as an end in itself. In Fig. 153(*a*) a power station is shown feeding a number of transforming stations by means of h.t. lines. From each transformer station, several l.t. lines are distributing the energy in the respective district of a densely populated area. Each district depends entirely upon one h.t. feeder. Each individual transformer station may be of moderate size, so that it is beyond economic possibility to provide sufficient means to make sure of uninterrupted supply to each consumer, e.g. by dual transmission lines, as indicated in Fig. 153(*b*). It is obvious that a

scheme as in Fig. 153(*b*) would result in increased reliability over a simple arrangement as per Fig. 153(*a*), but in the event of a heavy l.t. fault, it might be expected that both transformers feeding into one district would be thrown out of action, so that

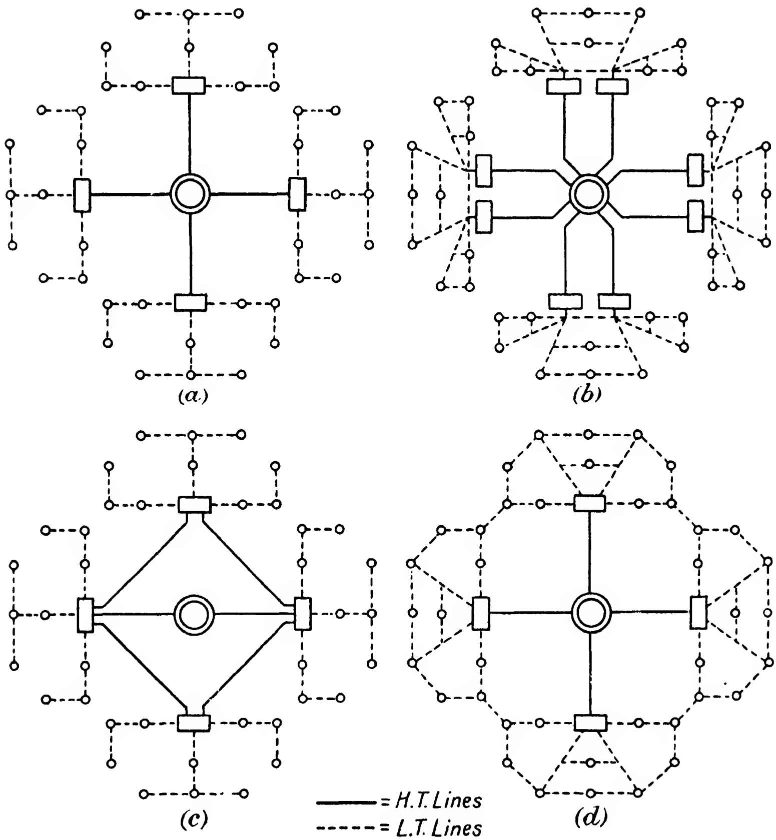


FIG. 153. SCHEMATIC DIAGRAMS OF ALTERNATIVE LAY-OUTS FOR POWER DISTRIBUTION

little would have been gained. On the other hand the cost of the whole distributing plant would be doubled. Assuming this to be prohibitive, let us consider alternative possibilities of improved safety.

In Fig. 153(*c*) a ring main system is introduced for the h.t. network. Though the total length of lines is less than twice

that of Fig. 153(*a*), every transformer is connected to two alternative paths of h.t. supply. Here again, however, a heavy l.t. fault may easily result in the transformer station affected being isolated from the power station. Failing alternative means, the whole district would thereby be robbed of its supply. Taking into account the increased number of circuit-breakers and the more elaborate means required for adequate protection of a ring main system, the cost of h.t. distributing plant would easily be three times that of Fig. 153(*a*).

Turning now to the l.t. network, a fault near a transformer station is liable to cause the cutting-off of the supply to all consumers connected to the same feeder. The provision of dual l.t. lines as in Fig. 153(*b*) eliminates this risk. The thorough interconnection into l.t. grids (Fig. 153(*d*)) covering reasonably wide areas, suggests itself as a further promising measure of improvement. In such a solidly interlinked network several alternative paths are always available for each consumer, even in the event of one or several transformer stations being cut out. All ensuing technical problems having been solved (see Chapter VIII), it follows that the interconnection on the l.t. side, a measure that can be realized with comparatively small outlay of capital, is, under given conditions, a far more effective means towards making the current supply more reliable, than even the most elaborate and costly modification of the h.t. system. Ordinary single feeders, without automatic switchgear in the transformer stations and with simple protective relays or fuses, will fully meet the demand on the h.t. side. This part of the scheme may intentionally be made the "weak spot" in favour of increased precautions against possible breakdowns in the power station and the l.t. network. This, of course, does not imply that a system of the kind referred to above is generally applicable. It is, in fact only suitable for densely populated urban areas. In rural districts conditions are reversed; there a highly reliable interconnected high tension network with open low tension feeders (Fig. 158 (*c*)) is to be advocated. The principle, however, is identical: to use intelligent discrimination in planning the protective gear. The reliability (and, incidentally, the economy) of the combined plant is thereby greatly improved even as compared with a system having the highest possible uniform factor of safety throughout all its sections.

In applying similar considerations to the various components

of electric plant and to the conditions influencing their layout, many valuable conclusions have been reached, some of which have been referred to in preceding Chapters.

Future Extensions. When planning protective gear, due consideration should be given to future extension. A feeder is always a prospective link in a future ring mains system, and by protecting it from the outset with gear applicable for dual feeding, costly future alterations may be avoided. The rupturing capacity of circuit-breakers should be such as to permit reasonable extensions to the plant. Petersen coils are also usually rated 25 or 30 per cent greater than would be required at the time of their installation.

Conclusions. Most transmission lines above 50 kV serve as bus-bars interlinking power stations. Faults on these lines are comparatively rare. Here, the maintenance of stability is the foremost object of protection.

As regards short-circuit protection of large transmission systems, the last word has certainly still to be spoken. None of the available methods is free from disadvantages. Differential protection does not safeguard the bus-bars and requires pilot wires and additional back-up relays. The directional balance system, otherwise perfect, still requires pilot wires, although the latter may be avoided if high frequency carrier-current transmission is used. This suggests itself where the same means is employed for the purpose of remote control. On the other hand high-speed distance protection which does not require pilots and extends protection to the bus-bars and to neighbouring sections without additional gear, cannot be made to operate instantaneously under all circumstances.

An important point in favour of distance relays is the fact that identical relays may be used for the protection of alternators, transformers and feeders, so that supervision and maintenance are substantially simplified. For plant of medium size, and in particular for h.t. distribution networks, all advantages appear to be on the side of distance protection. For medium voltage lines, apart from those coupling two power stations, stability problems are as a rule of minor importance.

By adopting the principle of solid interlinking over wide areas for the purpose of l.t. distribution, the uninterrupted supply of energy to consumers is achieved to perfection, even in the event of several h.t. feeders being thrown out of action. As has been shown in Chapter VIII, this system also

renders the installation of automatic h.t. switchgear in distribution sub-stations unnecessary; hence, there is no longer a reason against the direct connection of such stations to 33 kV, and a further intermediate voltage of 6 or 11 kV can be eliminated, where an interconnected l.t. network is applicable.

In a suitably protected system, continuity of supply to the consumer is assured except in two contingencies; the first is a fault at or near a consumer's own premises. For all practical purposes it is immaterial to the user, and in particular to the domestic current consumer, whether a failure is due to a breakdown in the power station, or to the blowing of a sub-circuit fuse. The user's main concern is that the current shall not fail at all, or if it does, that it shall be restored without delay. Therefore, the policy adopted by a number of supply undertakings of advocating, in some cases making compulsory, the use of circuit-breakers instead of fuses seems wise, and has met with great success.

Communication Equipment. The second cause of an interruption is the simultaneous breakdown of several power stations feeding into the same system. Such an occurrence may result either from a failure of protective gear, or from a combination of other exceptional and unforeseen circumstances. In this case, the maintenance of continuity rests on the last line of defence: the human element. To this element little is left in the normal operation of modern plant, except to decide which of the component parts are to be on, and which off duty, and to keep them all in perfect condition; also certain actions which are beyond the scope of the protective gear. These are, in the first line, the regrouping of generating power and distributing channels to cope with load conditions, in the event of, or shortly after a breakdown. In large plant this task falls to the "load despatcher."

Though they cannot be included under the term "protective gear" and therefore fall outside the scope of this survey, the available means for communication between the central control room and the individual generating and transforming stations are here mentioned, on account of the great bearing they have on the reliability of every large power supply system in case of special emergency. If a central control room is connected with all important stations not only by telephone and remote position indicators, but also by remote control gear, interruptions of current supply may be, if not entirely avoided,

at least limited in extent and duration. Of course, most careful and experienced planning is required for remote control gear. If a remote load despatcher were allowed to interfere with switching operations in a power station, without being kept sufficiently up to date with local events, even more harm might be done than if the station were left alone. Remote control must, therefore, be limited to certain important circuit-breakers, regulators, etc., and must be combined with such remote indicating instruments as will enable the operator to decide correctly and swiftly on the operations required in case of an emergency.

The co-ordination of the human element with automatic protective gear is one, and not the least important, of the problems which must be studied from all aspects when the protective arrangements are being planned. To relieve operating engineers of as much of their task as can conveniently be taken over by self-operating auxiliary devices such as automatic synchronizing gear, frequency regulators and automatic disturbance recorders, is certainly taking a step in the right direction; but the engineer on duty at the main control room should have adequate facilities at his disposal for obtaining, reliably and quickly, information of all important events, and for rendering assistance in cases of exceptional emergency.

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DISTANCE PROTECTION

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